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DEVELOPMENT OF THERMOPLASTIC
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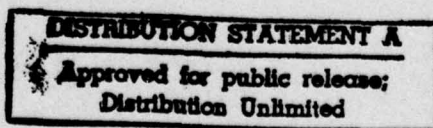
FINAL REPORT

Contract N62269-75-C-0386

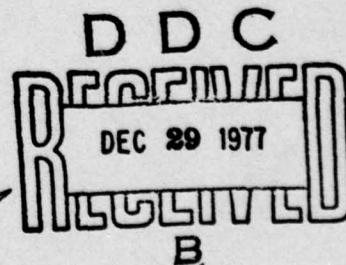
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General Dynamics Corporation
San Diego, California

for the

Naval Air Development Center
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This work accomplished the design, fabrication, and testing of structural panels of representative thermoplastic construction suitable for use in the forward fuselage areas of advanced CTOL and V/STOL carrier-based Naval aircraft.		

NADC-77187-30

FOREWORD

The work reported here was performed under the sponsorship of the Naval Air Development Center, Warminster, Pennsylvania. Mr. Murray Rosenfeld was the NADC Project Engineer.

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CONTENTS

<u>Section</u>		<u>Page</u>
1	INTRODUCTION	1
2	DETAILED TASK DESCRIPTION	3
	2.1 SUBCOMPONENT DESIGN	3
	2.2 SUBCOMPONENT FABRICATION	3
	2.3 SUBCOMPONENT TESTING	4
	2.4 COST EVALUATION	4
3	COMPONENT DESIGN	5
4	CONSOLIDATION STUDIES	7
	4.1 PREPREG CONSOLIDATION REQUIREMENTS	7
	4.1.1 Removal of Adsorbed Moisture and Solvents	7
	4.1.2 Softening Thermoplastic Resin	7
	4.1.3 Avoiding Resin/Fiber Decomposition	7
	4.1.4 Consolidating Prepreg Plies	9
	4.1.5 Solidify the Laminate	9
	4.2 PROCESS REQUIREMENTS BRACKETING — DETER-	9
	MINATION OF THE CONSOLIDATED TEMPERA-	
	TURE RANGE	
	4.2.1 Thermal Mechanical Analysis	9
	4.2.2 Thermal Gravimetric Analysis	9
	4.3 EXPERIMENTAL PLAN FOR DETERMINING	11
	OPTIMUM CONSOLIDATION PRAMETERS	
	4.4 EFFECT ON CONSOLIDATION TEMPERATURE	15
	ON MECHANICAL PROPERTIES	
	4.5 EFFECT OF CONSOLIDATION PRESSURE ON	15
	MECHANICAL PROPERTIES	
	4.6 EFFECT OF DWELL TIME ON MECHANICAL	15
	PROPERTIES	
	4.7 TEMPERATURE-PRESSURE-TIME OPTIMUM	17
	PROPERTIES ZONE	
	4.8 CONSOLIDATION PROCESSING RECOMMEN-	17
	DATIONS	

CONTENTS (Cont'd)

<u>Section</u>		<u>Page</u>
5	TOOLING MATERIAL EVALUATION	19
	5.1 THERMOSET PLASTIC	22
	5.2 MACHINED BULK GRAPHITE	22
	5.3 ELECTROFORMED NICKEL	25
	5.4 CONCRETE	25
	5.5 METAL	27
	5.6 CERAMIC	27
6	DEMONSTRATION ARTICLE TOOLING SELECTION	30
7	JOINING STUDIES	38
8	DEMONSTRATION ARTICLE FABRICATION	42
	8.1 INTRODUCTION	42
	8.2 CURVED CHANNEL FORMING	42
	8.3 SKIN AND SKIN DOUBLER FORMING	42
	8.3.1 Preforming	44
	8.3.2 Final Forming	44
	8.4 SKIN/SKIN DOUBLER ASSEMBLY	48
	8.5 BEAM TRIMMING	48
	8.6 DOOR ASSEMBLY	48
9	ECONOMIC ANALYSIS	51
	9.1 METAL DOOR	51
	9.1.1 Description	51
	9.1.2 Manufacturing Facilities	51
	9.1.3 Tooling	51
	9.1.4 Manufacturing Sequence	52
	9.1.5 Average Cost of Metal Door	52
	9.2 COMPOSITE DOOR	52
	9.2.1 Description	52
	9.2.2 Manufacturing Facilities	52
	9.2.3 Tooling	52
	9.2.4 Manufacturing Sequence	53
	9.2.5 Average Cost of Composite Door	53
10	CONCLUSIONS AND RECOMMENDATIONS	54
<u>Appendix</u>		
A	COMPOSITE WEAPONS BAY DOOR ANALYSIS	A-1

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
3-1	F-16 Metal Ammunition Bay Door	5
3-2	Demonstration Component Design	6
4-1	Resin Softening Point of Hercules AS/3004 Prepreg	10
4-2	Volatiles Outgassing Behavior of Hercules AS/3004 Prepreg	10
4-3	Thermal Gravimetric Weight Loss Study on 12-Ply Hercules AS/3004 Prepreg (41% Resin Content)	11
4-4	Processing of AS/3004 Thermoplastic	12
4-5	Ply Location and Orientation	13
4-6	Specimen Location	14
4-7	Effect of Consolidation Temperature on Flexural Strength	15
4-8	Effect of Consolidation Pressure on Flexural Strength	16
4-9	Effect of Dwell Time on Flexural Strength	16
4-10	Optimum Properties Consolidation Pressure-Temperature Zone	18
5-1	Strake Tool	20
5-2	Corrugated A-S/Polysulfone Laminate in Matched-Metal Die Set	21
5-3	Bulk Graphite Tooling	23
5-4	Part Formed on Machined Bulk Graphite Tooling	24
5-5	Electroformed Inlet Leading Edge	26
5-6	Ceramic/Nickel Compatibility Samples	28
6-1	Channel Form Tool	31
6-2	Thermoplastic Form Tool - Skin 72C0581-101A	32
6-3	Thermoplastic Form Tool - Skin 72C0581-101B	33
6-4	Thermoplastic Form Tool - Skin 72C0581-101A	34

LIST OF FIGURES (Cont'd)

<u>Figure</u>		<u>Page</u>
6-5	Curve Channel Form Tool	35
6-6	Ammunition Bay Door Male Skin Tool	36
6-7	Ammunition Bay Door Female Skin Tool	37
7-1	Single Spotweld Specimen, Type A	38
7-2	Double Spotweld Specimen, Type B	39
7-3	Bolted Joint Specimen, Type D	39
8-1	Formed Curved Channels	43
8-2	Four Formed Skins	45
8-3	Front of Formed Skin	46
8-4	Back of Formed Skin	47
8-5	Completed Ammunition Bay Door Assembly, Front	49
8-6	Completed Ammunition Bay Door Assembly, Back	50

LIST OF TABLES

<u>Table</u>		<u>Page</u>
4-1	Consolidation Process Requirements	8
7-1	Specimen Dimensions	40
7-2	Lap Shear Strength (pounds)	40
7-3	Multiple Spotwelds	41
7-4	Bolted Specimens (Single Mechanical Fastener)	41

SECTION 1

INTRODUCTION

Initial work on thermoplastic materials centered on their use as adhesives for graphite-reinforced epoxy materials. This, in turn, led to the investigation of thermoplastic as a resin in the composite as opposed to the more conventional thermosetting resins. Initial studies have shown that the mechanical and structural properties of thermoplastic composites are comparable with the corresponding epoxy systems.

There is an opportunity for significant cost savings by using thermoplastic resins instead of thermosetting resins.

First, there is a small potential cost savings in the raw material because the thermoplastic molding compounds are generally less expensive than the epoxies. Secondly, virtually all the composite material purchased can be utilized as there is no bleedout of resin, there are no volatiles to be removed, and any scrap can be reused as molding materials. There is no need for special cure cycles and specific heating and cooling rates. The material is not cured but consolidated, a process which can be accomplished by the application of 600 to 650F and from 100 to 200 psi pressure for a few minutes.

Flat panels of material, either consolidated or simply tacked together, can be formed into complex shapes in matched dies. Previous programs have shown that the cost of tooling and the choice of tooling are significant factors in the total cost of finished thermoplastic composite parts.

It is the objective of this program to extend the developments already accomplished in graphite/thermoplastic materials to the general area of stiffened, curved fuselage structural panels for advanced Navy aircraft. The approach was to design, fabricate and test panels of representative construction suitable for use in the forward fuselage areas of advanced CTOL and V/STOL carrier-based Naval aircraft.

SECTION 2

DETAILED TASK DESCRIPTION

This section describes details of the tasks accomplished in the Development of Thermoplastic Composite Aircraft Structural Elements contract.

2.1 SUBCOMPONENT DESIGN

A section of the fuselage from an advanced fighter aircraft was selected for study. Conceptual designs for frame stiffened panels were made using graphite/thermoplastic. A typical panel element was selected and detailed for fabrication and testing.

2.2 SUBCOMPONENT FABRICATION

Representative panel specimens were tooled and fabricated for test using available Type A-S/polysulfone graphite/thermoplastic material. Current fabrication techniques were extended or improved to accomplish high-quality specimen fabrication. The fabrication development and detail fabrication task accomplished included:

- a. Fabricate four 18-inch by 18-inch panels of A-S/P1700 in a $(0 \pm 45)_{s3}$ (18 ply) laminate. These panels were shipped to NADC for evaluation.
- b. Joining Development. A series of joint specimens were fabricated and tested to evaluate spotwelding of graphite/thermoplastic in comparison with bolted joints. Single and double spotwelded specimens were tested. Before fabrication and testing of these specimens, optimum weld parameters were developed.

To serve as a baseline, several bolted joint specimens were fabricated and tested. Specimens were serialized. The first specimen of Type A1 was a static specimen identified as A1S. The third fatigue specimens of Type A8 were identified as A8F3.

- c. Curved Stiffener Fabrication Such as Rings and Frames. Methods of post-forming such sections from flat sheet and straight hat and I-sections were developed and demonstrated.

- d. Panel Post-Forming Molds. The current heated ceramic dies are expensive, fragile, and bulky. Simple molds using cast metal, machined bulk graphite, and high-temperature silicone rubber were investigated for curved panel post-forming.

2.3 SUBCOMPONENT TESTING

Specimens for static and fatigue testing were prepared from the panels fabricated in Task 2. The following specimens were tested:

- a. Sixteen static and 49 fatigue joining specimens.
- b. Five curved stiffened panels, 26 x 45 inches, were fabricated. Testing to determine buckling strengths and post buckling behavior in shear and compression will be accomplished by NADC and will be reported in a separate report.

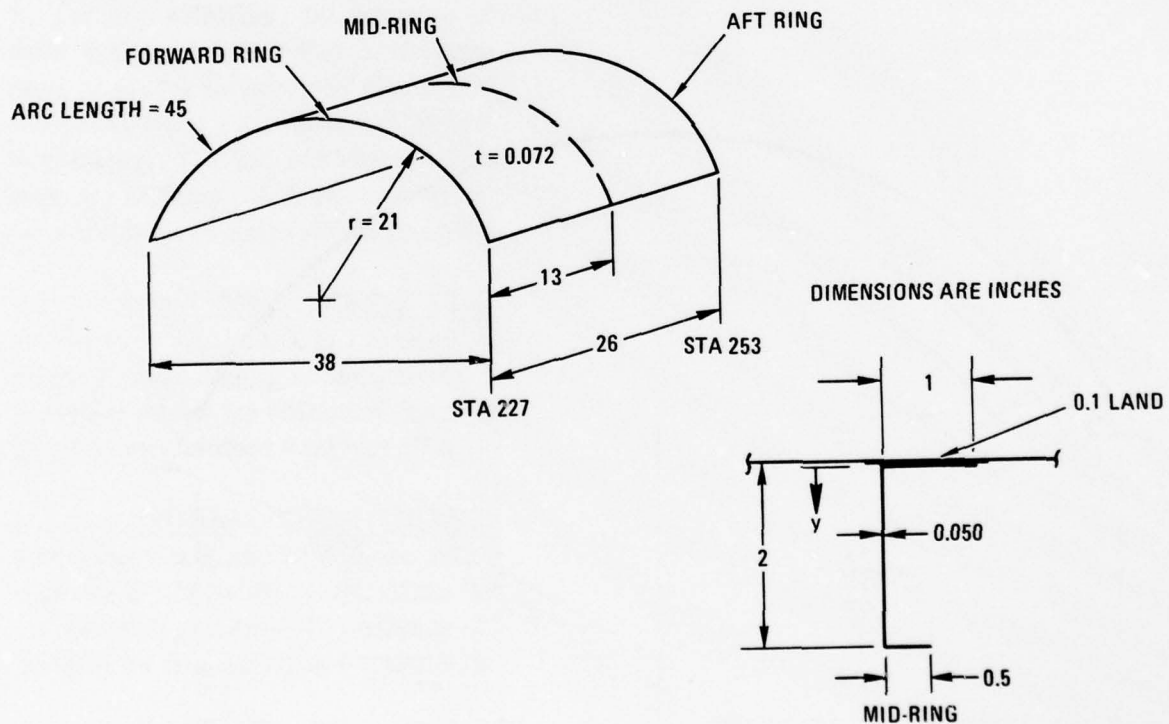
2.4 COST EVALUATION

Manufacturing and tooling cost records were collected, tabulated, and evaluated throughout the design and fabrication tasks to provide a factual base for component cost predictions in Task 3.

SECTION 3

COMPONENT DESIGN

The component selected for the graphite/thermoplastic program was the F-16 aircraft ammunition bay door, which is an aluminum alloy structure. The actual critical loading is internal pressure. However, for the purpose of the present program the component is assumed to be loaded in shear only. Consequently, the graphite/thermoplastic door was designed to have equivalent shear buckling strength as its metal counterpart. The mid-ring must be sufficiently rigid so that shear buckling is confined to the individual panels. The allowable shear flow governed the design of the edge members. Appendix A of this report details the analysis leading to our final design. The ammunition bay door design is shown in Figure 3-1. Figure 3-2 is the detailed drawing of the door.



Material:

2024-T62

$E = 10.5 \times 10^6$

$\gamma = 0.33$

Figure 3-1. F-16 Metal Ammunition Bay Door

NOTES:
 11 LOCATION OF NO. 1 PLY OPTIMAL.
 12 PRIMARY BOND - 2 TO -3, MAKE -S.
 13 SECONDARY BOND - 4 TO -5 WITH
 EA9309 ADHESIVE.

MIN THICKNESS-.050		
10 PLYS		
PLY NO.	ORIENTATION	Ø
1	45°	
2 & 9	135°	
3 & 8	0°	
5 & 6	90°	
10	45°	

PLY LAY UP TIE
 BLK FOR -4
 NOTE 11 NO SCALE

MIN THICKNESS-.075		
15 PLYS		
PLY NO.	ORIENTATION	Ø
1	45°	
2, 4, 12	135°	
3 & 14	45°	
5 THROUGH	0°	
15	45°	

MIN THICKNESS-.025		
5 PLYS		
PLY NO.	ORIENTATION	Ø
1	45°	
2	135°	
3	0°	
4	135°	
5	45°	

PLY LAY UP TAB FOR -1, -2
 NOTE 11 NO SCALE

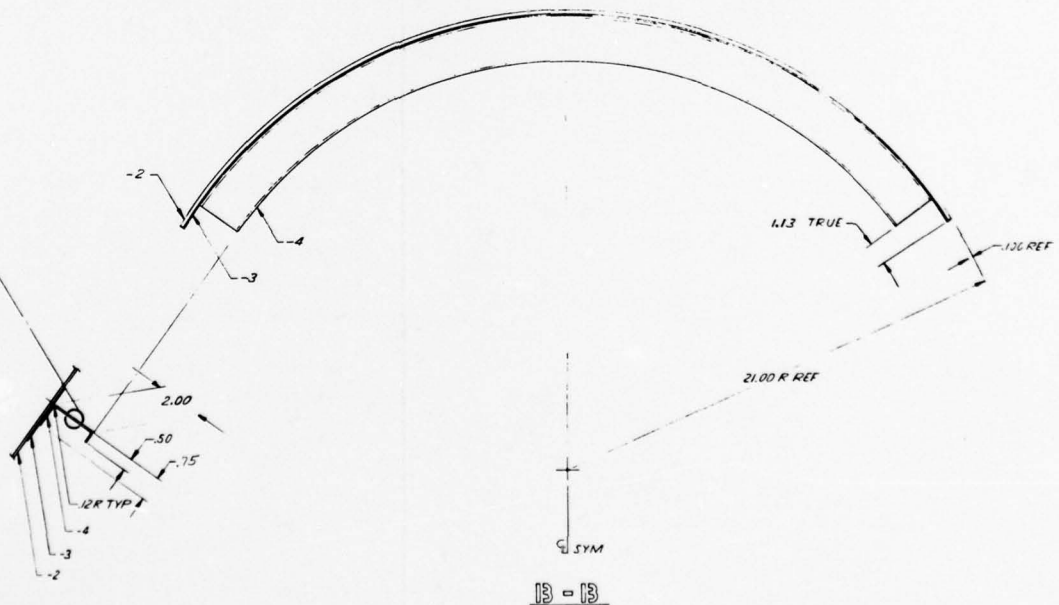


Figure 3-2. Demonstration Component Design



SECTION 4

CONSOLIDATION STUDIES

4.1 PREPREG CONSOLIDATION REQUIREMENTS

4.1.1 REMOVAL OF ADSORBED MOISTURE AND SOLVENTS. The manufacture of polysulfone prepreg requires dissolution of the resin in methylene chloride. Approximately 4 to 5% of the prepreg weight consists of this solvent and a variable amount of water, which is adsorbed during the prepregging operation or subsequently during storage and layup. This volatiles fraction, solvents and water, must be removed before the consolidation step or it will be trapped as a gaseous phase in the laminate. Extensive work on graphite/epoxy structures has shown the highly degrading influence the presence of voids has on mechanical properties (Reference 1). Preliminary data suggest similar behavior for graphite/thermoplastic laminates.

To remove volatiles, the prepreg must be heated to some elevated temperature beyond their boiling points. For laminates more than a few plies thick, vacuum is normally used to assist in volatiles elimination. Section 4.2.2 describes thermal gravimetric analysis (TGA) studies on AS/3004 which provide temperatures for completion of volatiles outgassing, T_V , for various heating conditions. Table 4-1 summarizes this together with the various other process requirements and operational steps needed to accomplish consolidation of polysulfone prepreg.

4.1.2 SOFTENING THERMOPLASTIC RESIN. A second consolidation requirement as shown in Table 4-1 is the need to soften the thermoplastic resin so that the various prepreg plies can be consolidated. To accomplish this, the prepreg layup must be heated to above its softening temperature T_S . Section 4.2.1 describes the results of a thermal mechanical analysis (TMA) study to determine the resin softening point.

4.1.3 AVOIDING RESIN/FIBER DECOMPOSITION. Heating the prepreg so as to soften the resin and to remove volatiles should occur below a temperature that will degrade the fiber or resin. This decomposition temperature, T_D , can be determined via thermal gravimetric analysis (TGA) through detection of decomposition weight loss, and will be described in Section 4.2.2.

-
1. Yokota, M. J., "Low-Cost Manufacturing Techniques for Composites — In-Process Control of Resin Curing," CASD-ERR-75-040, General Dynamics Convair Division, December 1975.

Table 4-1. Consolidation Process Requirements

Processing Requirement	Operation Steps	Data Required	Experimental Technique
1. Remove adsorbed moisture and solvents	Heat above outgassing temperature (vacuum)?	Volatiles outgassing temperature T_V	Thermal gravimetric analysis (TGA)
2. Soften thermoplastic resin	Heat above resin softening temperature	Resin softening temperature T_S	Thermal mechanical analysis (TMA)
3. Avoid resin/fiber decomposition	Do not heat above resin/fiber decomposition temperature	Resin/fiber decomposition temperature T_D	Thermal gravimetric Analysis (TGA)
4. Consolidate prepreg plies	Apply pressure in excess of stacking friction of plies and viscosity of resin	Minimum consolidation pressure P_C Minimum consolidation temperature T_C	Consolidation pressure versus consolidation temperature
5. Solidify laminate	Cool to below resin softening temperature	Resin softening temperature T_S	Thermal mechanical analysis (TMA)

4.1.4 CONSOLIDATING PREPREG PLIES. Between the resin/fiber decomposition temperature and the temperature for completion of volatiles outgassing is the temperature range available for prepreg consolidation. The minimum temperature and pressure requirements for producing optimum properties in this temperature range must be determined through test laminate fabrication and will be described in Section 4.5.

4.1.5 SOLIDIFY THE LAMINATE. During the actual consolidation phase of processing, the resin is in a glassy liquid state. The resin must be cooled to below its glass transition temperature or its resin softening temperature, T_S , to solidify and complete the consolidation of the laminate. The determination of the resin softening temperature is described in Section 4.2.1.

4.2 PROCESS REQUIREMENTS BRACKETING — DETERMINATION OF THE CONSOLIDATED TEMPERATURE RANGE

As pointed out in Section 4.1, several key temperatures must be determined so that a consolidation and forming temperature range can be logically selected for study. Once a consolidation temperature range has been established, consolidation pressures and dwell times can then be varied within this range and tested for producing optimum mechanical property levels. These studies are discussed in Sections 4.4, 4.5, and 4.6.

4.2.1 THERMAL MECHANICAL ANALYSIS. (TMA) A thermal mechanical analysis study was carried out to determine the resin softening point of Hercules AS/3004. The test determines this point by indicating the temperature that a weighted indenter begins to penetrate the prepreg sample. Figure 4-1 shows the effect that various indenter loads have on the resin softening temperature. The resin softening temperature is determined by extrapolating to zero indenter load. This value has been determined to be 350F and locates the very lowest temperature that can be used to consolidate a laminate of AS/3004.

4.2.2 THERMAL GRAVIMETRIC ANALYSIS. (TGA) The weight loss experienced by Hercules AS/3004 thermoplastic prepreg heated at 5F/minute is shown in Figure 4-2 and indicates two major volatiles loss regions. The first is centered at roughly 350F and the second occurs beyond 700F. The first volatiles loss peak results from methylene chloride and water outgassing. The second results from resin decomposition. Fiber degradation is also thought to occur in this temperature range and may explain the small difference between the prepreg versus the resin-only outgassing curve.

At the 5F/min heat-up rate of this test, the solvent-water outgassing is completed at 450F. Figure 4-3 shows how this temperature as well as the resin/fiber decomposition temperature can vary with heat-up rate. For the heat-up rate range of interest in autoclave and press operations, the consolidation temperature range is 450 to 700F. Note that the 450F lower temperature volatile outgassing boundary is 100 degrees higher than the resin softening temperature reported in Section 4.2, and therefore satisfies process requirement 2 of Table 4-1.

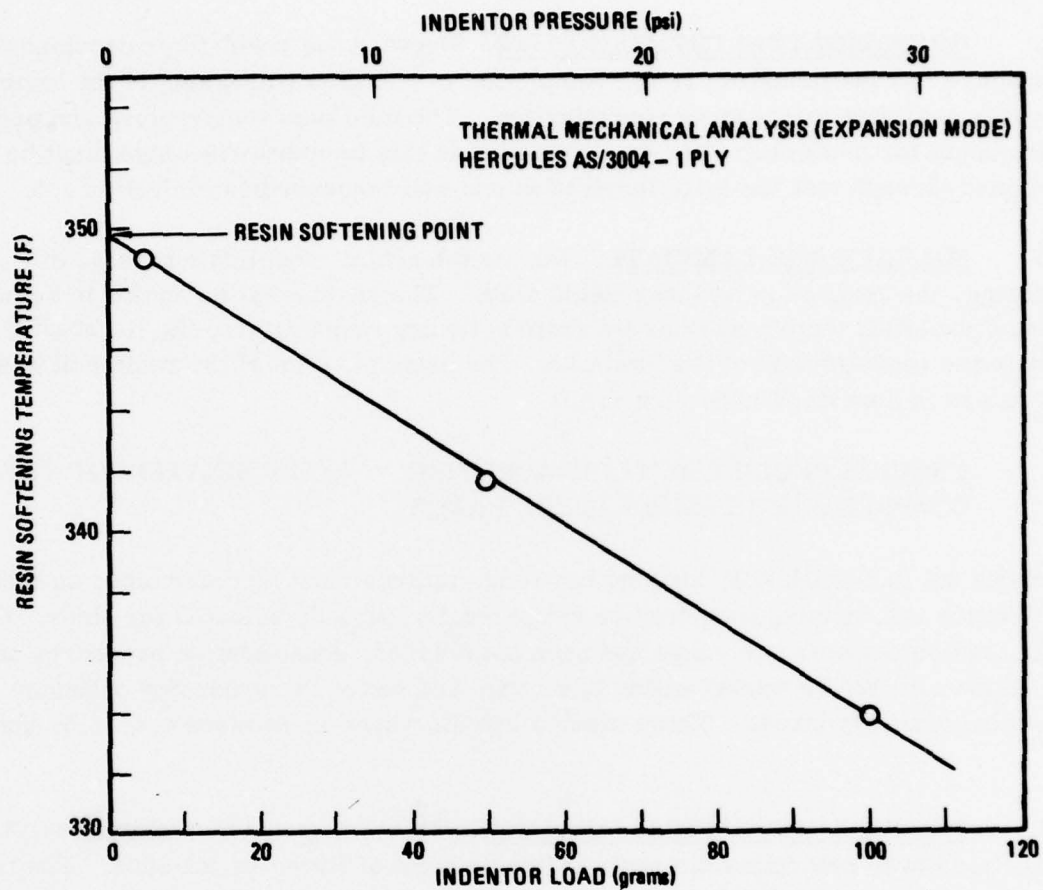


Figure 4-1. Resin Softening Point of Hercules AS/3004 Prepreg

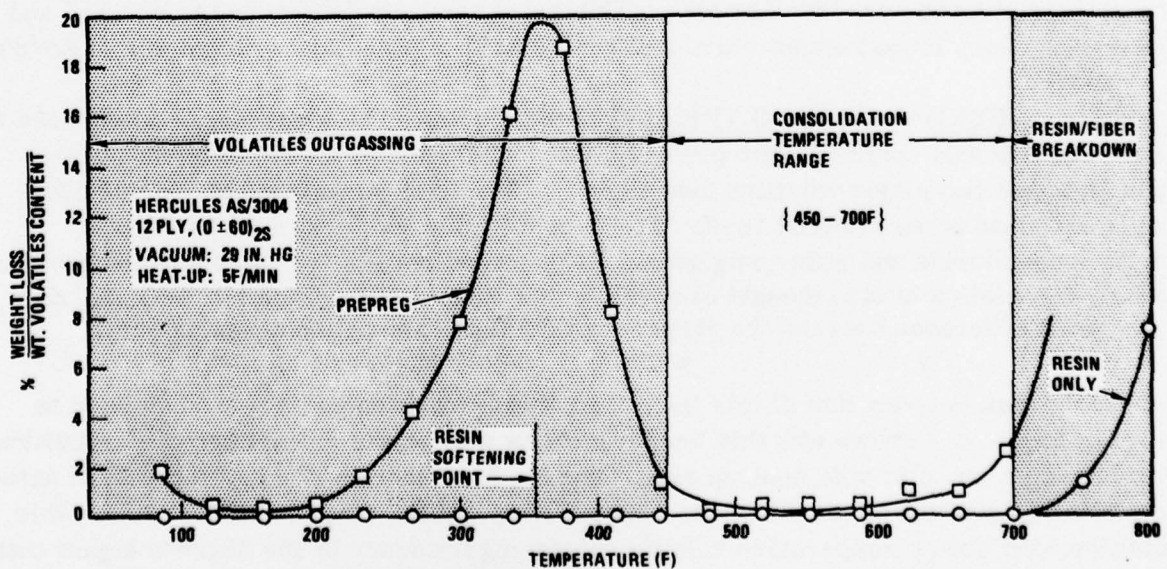


Figure 4-2. Volatiles Outgassing Behavior of Hercules AS/3004 Prepreg

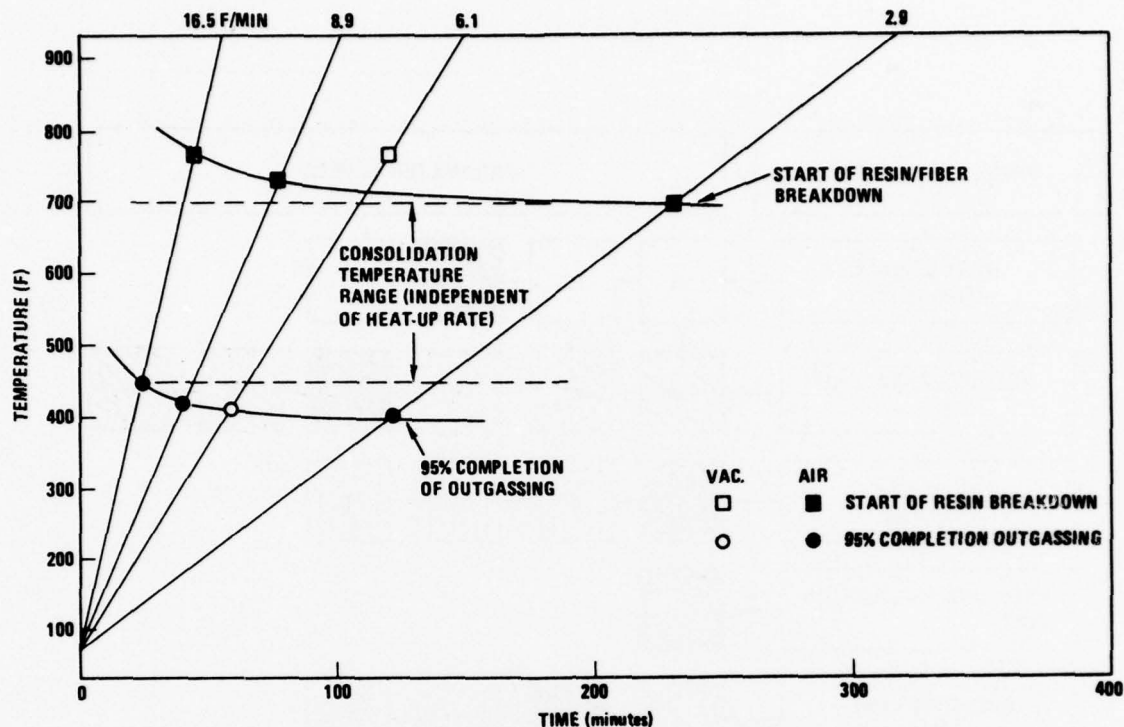


Figure 4-3. Thermal Gravimetric Weight Loss Study on 12-Ply Hercules AS/3004 Prepreg (41% Resin Content)

4.3 EXPERIMENTAL PLAN FOR DETERMINING OPTIMUM CONSOLIDATION PARAMETERS

Figure 4-4 shows a listing of process parameters and a number of parameter levels that are required for a complete optimization study. For this initial exploratory investigation, three process parameters were selected for study: consolidation temperature (between 450 and 700 F), consolidation pressure (50 to 200 psi), and dwell time (30 to 240 minutes) at the given consolidation temperature and pressure. For each of these tests the following remaining process variables were held constant:

Heat-up rate:	5 F/min
Pressure application point:	10 minutes into hold
Vacuum level:	29 inches Hg
Bleeder:	2 x 181 style glass cloth
Pressure source:	Autoclave
Cooldown rate:	10 F/min

The test panels were 6 by 12 inches by 12 plies $[0/\pm 60]_{2s}$. The ply location and orientation is shown in Figure 4-5; the specimen layout is shown in Figure 4-6.

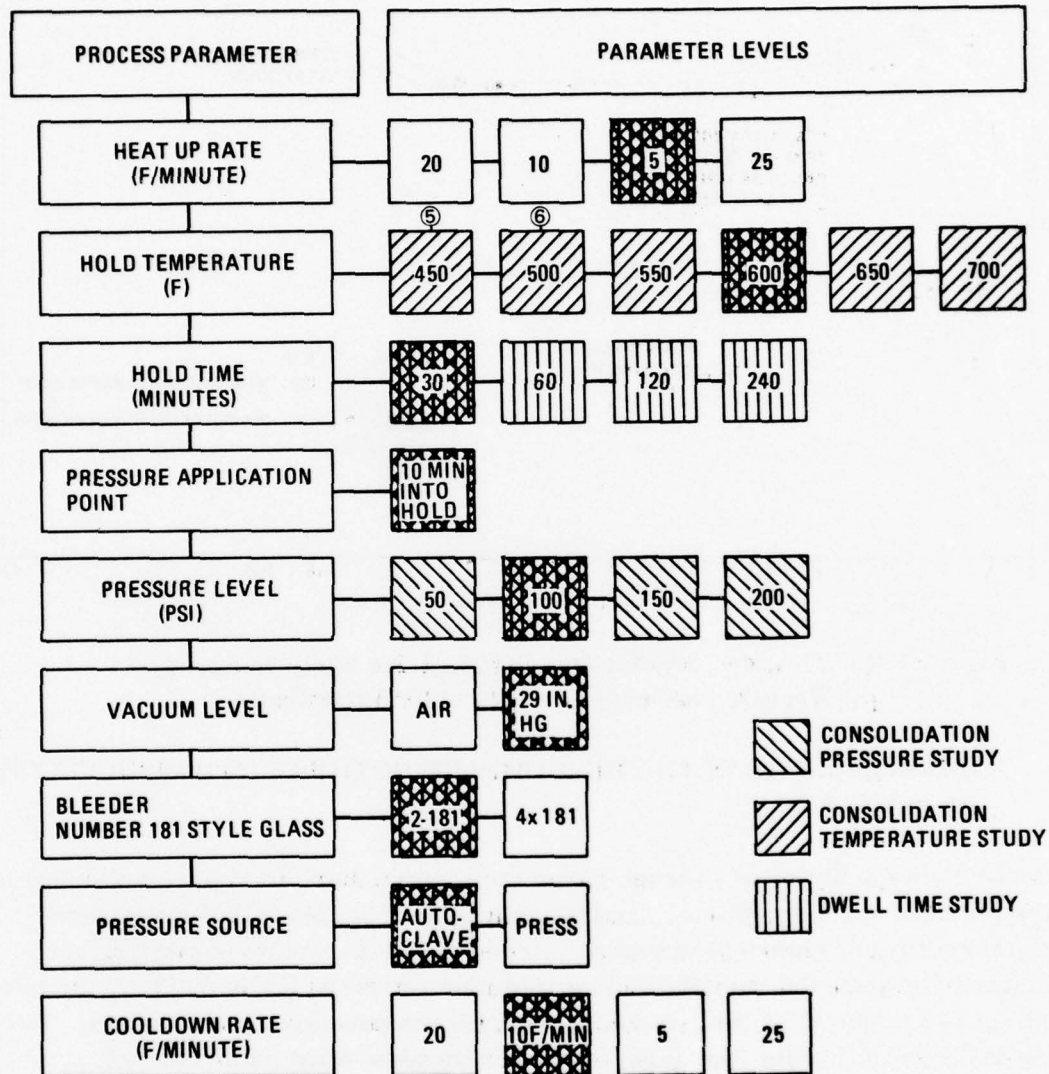


Figure 4-4. Processing of AS/3004 Thermoplastic

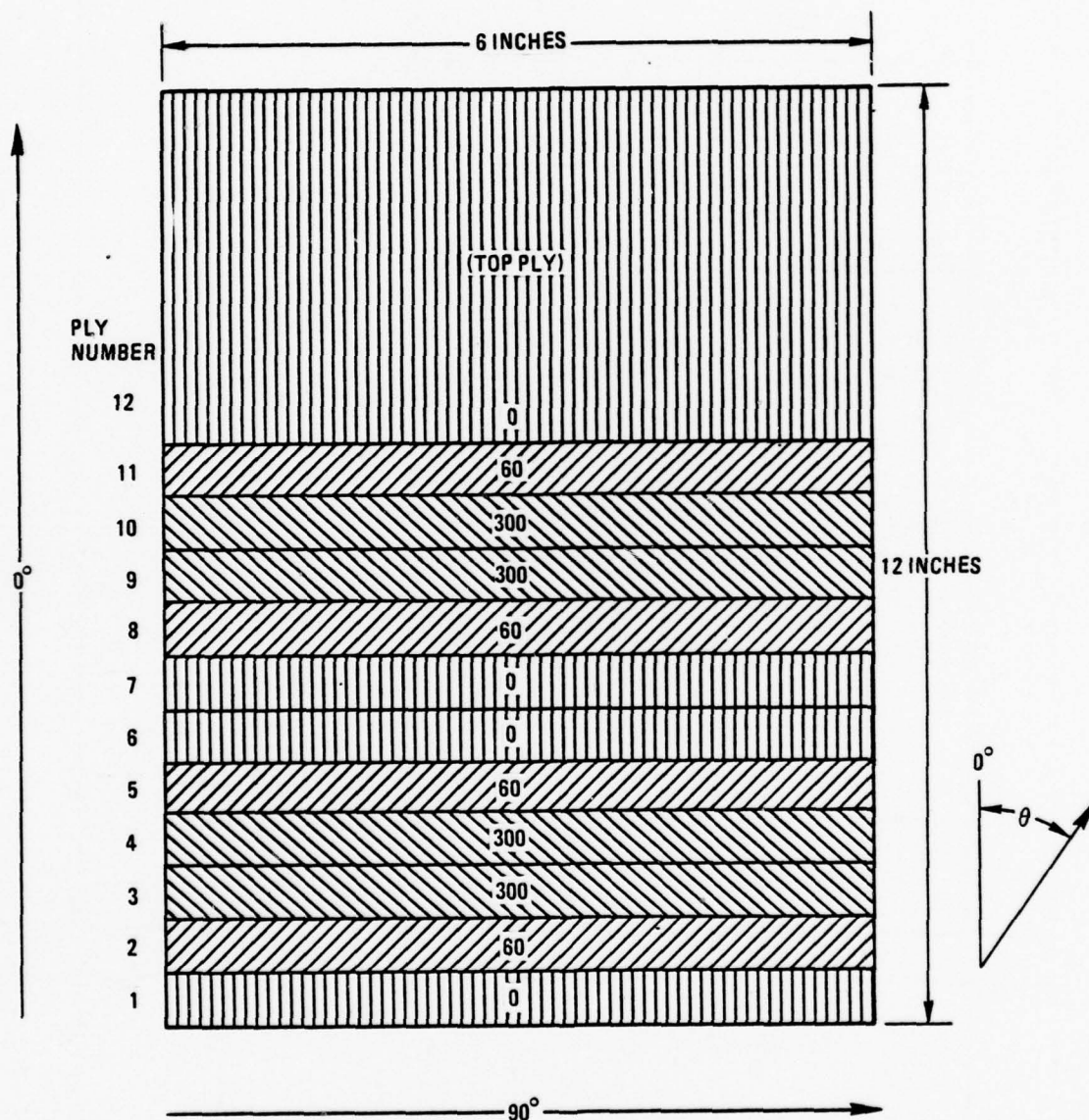


Figure 4-5. Ply Location and Orientation

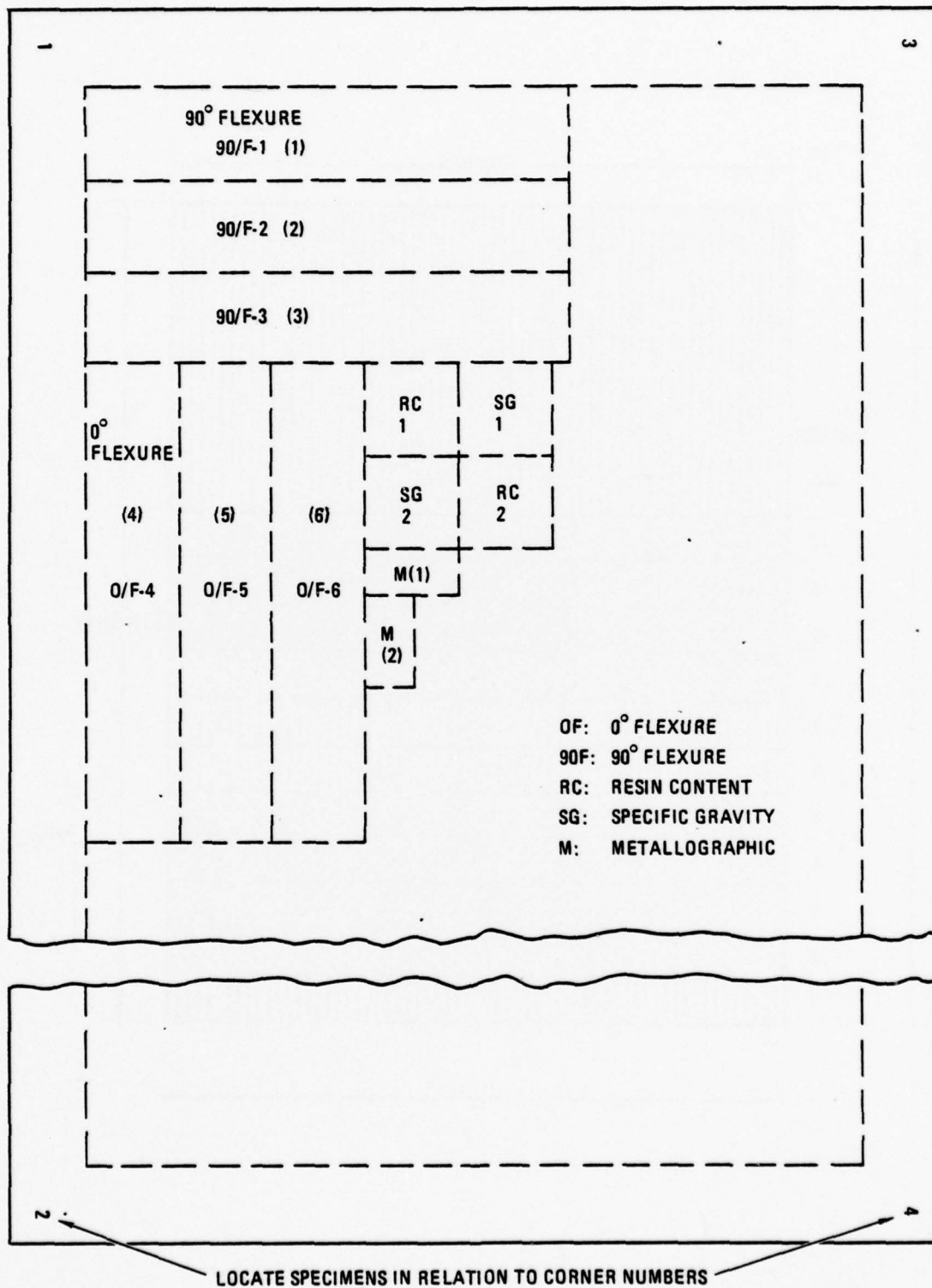


Figure 4-6. Specimen Layout

4.4 EFFECT ON CONSOLIDATION TEMPERATURE ON MECHANICAL PROPERTIES

Figure 4-7 shows the effect of consolidation temperature on flexure strength. In this series of tests the consolidation pressure was fixed at 100 psi. Note that for consolidation pressures restricted to 100 psi, the optimum properties consolidation temperature range is 600 to 700F. It should be pointed out that this temperature range should widen if higher consolidation pressures could be applied. The next section considers the influence of consolidation pressure on mechanical properties.

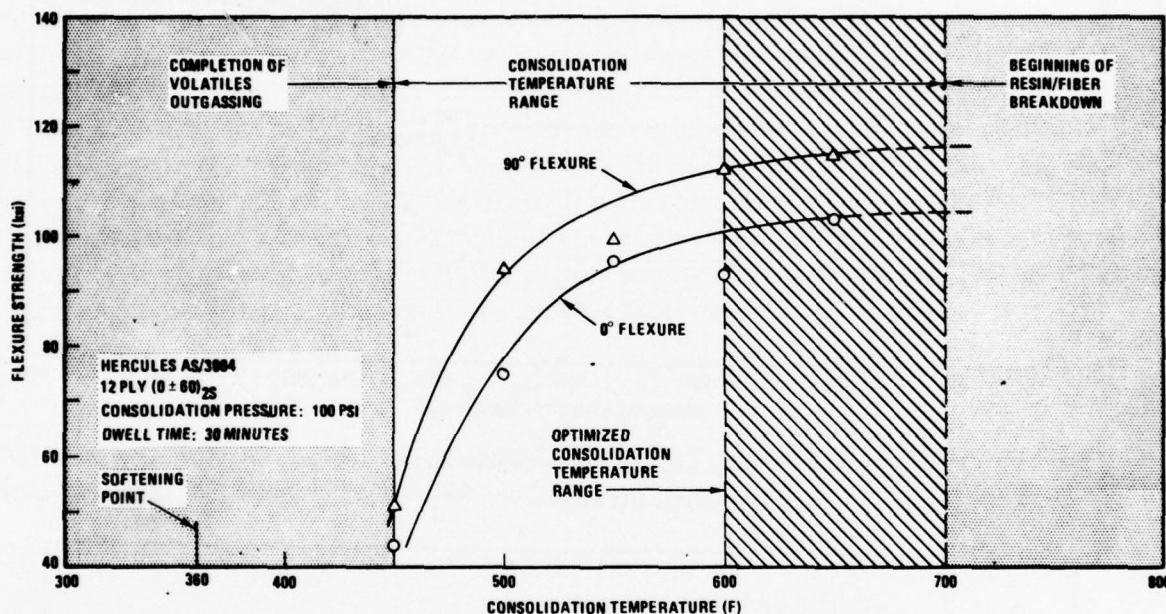


Figure 4-7. Effect of Consolidation Temperature on Flexural Strength

4.5 EFFECT OF CONSOLIDATION PRESSURE ON MECHANICAL PROPERTIES

Figure 4-8 shows the influence of consolidation pressure level on flexure strength for laminates processed at 600F. Notice that although the 90° flexural strengths are relatively unaffected by increasing consolidation pressure, the 0° flexures are greatly influenced by pressure. From 50 psi to 200 psi, the 0° flexural strength increased from 89 ksi to 116 ksi or roughly a 30% improvement. It is recommended that higher pressure levels be explored to determine the plateau pressure level requirement for optimum properties. For work at higher pressures, hydraulic presses are recommended since 200 psi is the upper practical limit for autoclaves.

4.6 EFFECT OF DWELL TIME ON MECHANICAL PROPERTIES

Figure 4-9 shows the effect of dwell time on flexural strength. For this series of experiments, consolidation temperature was fixed at 600F and consolidation pressure

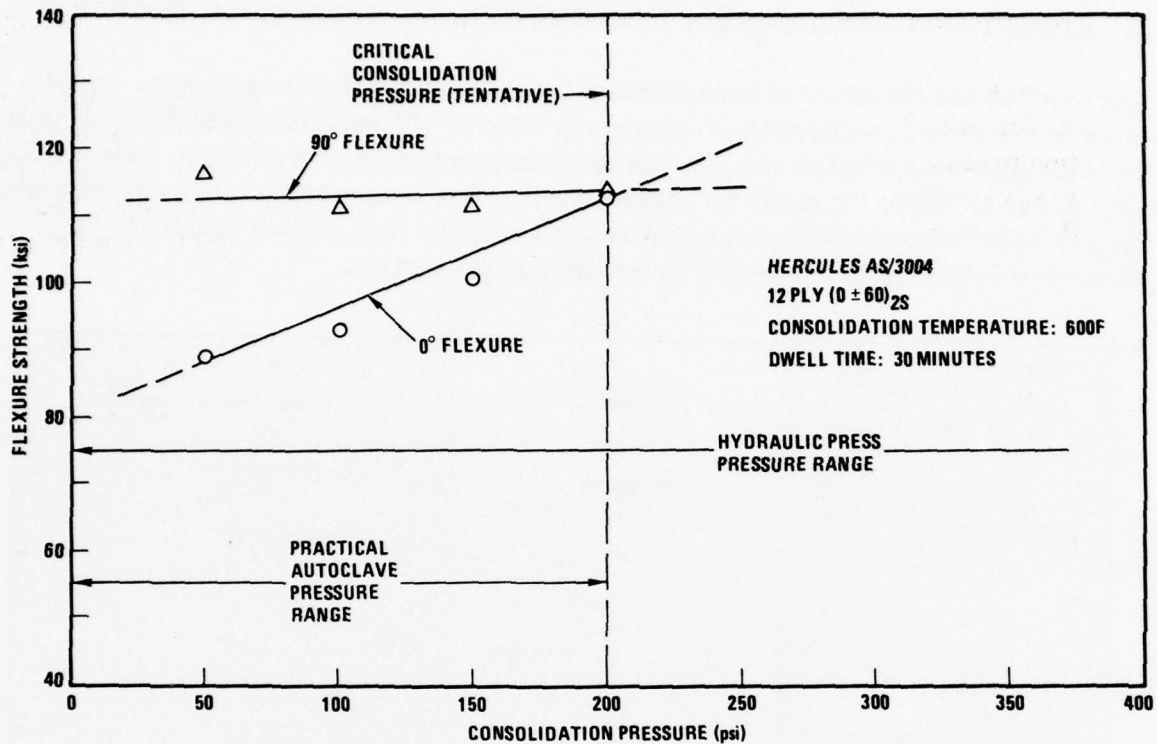


Figure 4-8. Effect of Consolidation Pressure on Flexural Strength

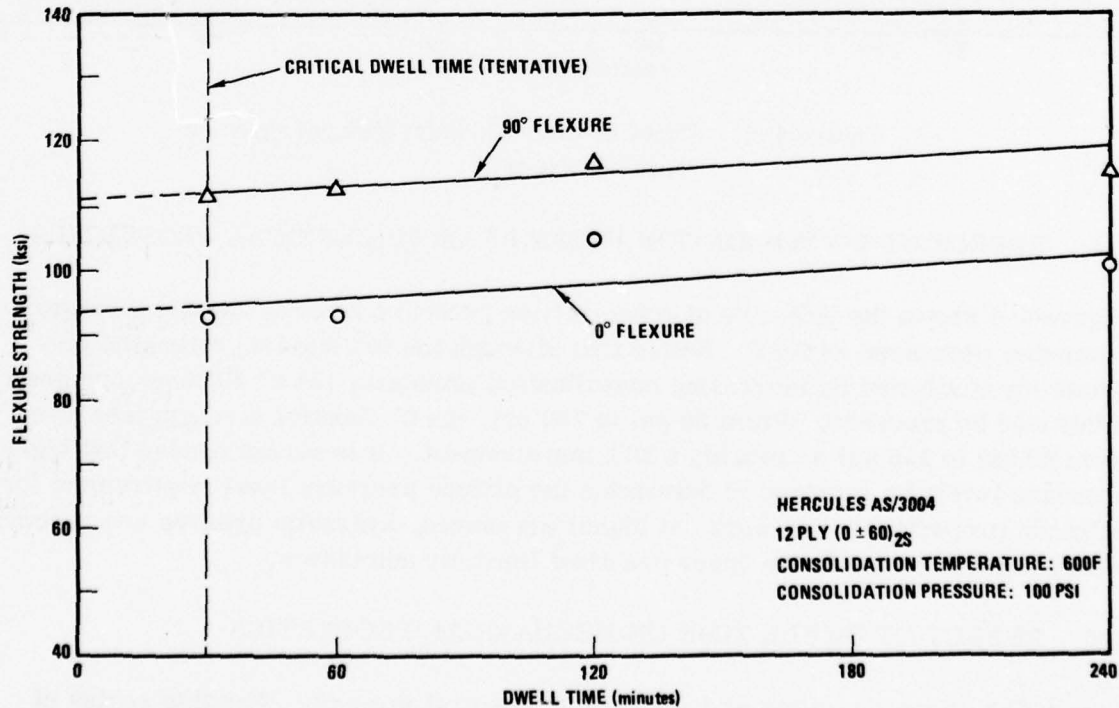


Figure 4-9. Effect of Dwell Time on Flexural Strength

at 100 psi. The data of Figure 4-9 suggests a tentative dwell time of 30 minutes. Additional data, however, for dwell times less than 30 minutes may show a shorter dwell time is permissible.

4.7 TEMPERATURE-PRESSURE-TIME OPTIMUM PROPERTIES ZONE

Combining the results of Sections 4.4, 4.5 and 4.6 and plotting the flexural strength results in pressure-temperature-time space, an optimum properties zone can be located. This zone, as shown in Figure 4-10, indicates that by applying higher pressures, lower consolidation temperatures can be used or conversely by using higher consolidation temperatures, lower pressures can be applied to achieve similar optimum properties. A final decision for production is made through a cost trade analysis that includes tooling and facilities limitations. As an example, if tooling materials should restrict processing temperatures to 450 or 500F, the plot of Figure 4-10 would suggest pressures greater than 200 psi would be needed, which would require use of a hydraulic press. On the other hand, if only autoclaves are available, Figure 4-10 would recommend that consolidation temperatures greater than 600F would be needed.

4.8 CONSOLIDATION PROCESSING RECOMMENDATIONS

With the present data base and utilizing an autoclave capable of 200 psi, the following consolidation processing recommendations are made:

- a. Apply full vacuum
- b. Heat-up rates 5 to 10F/min.
- c. Hold at between 650 and 670F.
- d. Apply 200 psi, 10 minutes into 650-670F hold.
- e. Hold for an additional 30-40 minutes.
- f. Cool under pressure at 5-10F/min to below 250F.
- g. Remove pressure.

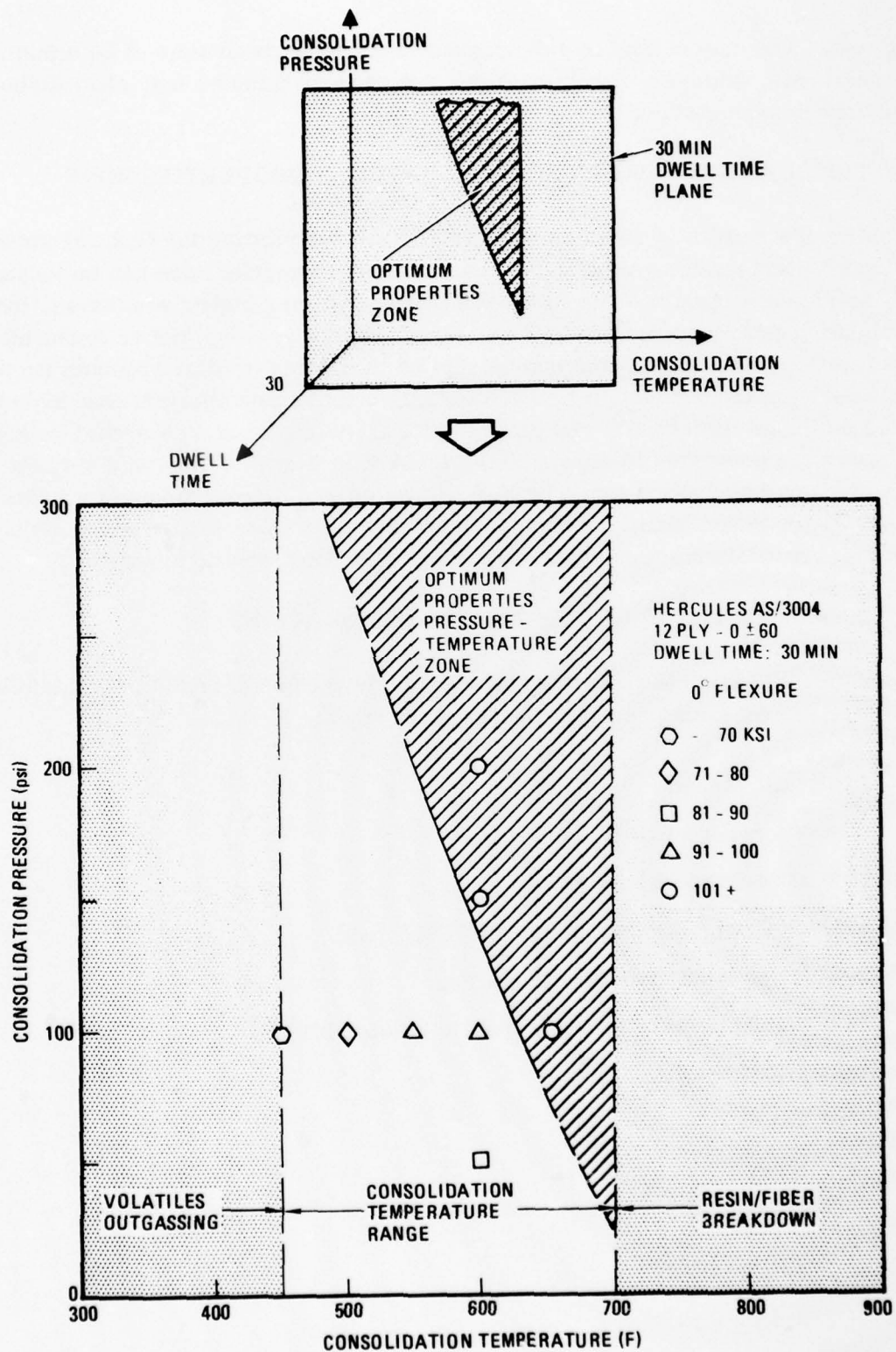


Figure 4-10. Optimum Properties Consolidation Pressure-Temperature Zone

SECTION 5

TOOLING MATERIAL EVALUATION

Solid-phase forming methods for graphite/thermoplastic materials vary from those established for solid-phase forming of thermoplastics. Low shear strength at elevated temperatures (above T_g) between plies causes separations during forming, using present methods established for thermoplastics. The low shear strength, however, allows the material to flow to the proper contour of the part to be formed without breaking the graphite fiber.

Hot forming tools with the capacity of controlled pressure application and rapid cooling have been developed and used successfully (Figure 5-1: strake tool — USAF Contract F33615-74-C-5086). This has allowed forming of parts between the melting point (T_m) and the glass transition temperature (T_g) while at the same time incorporating cooling systems that can rapidly cool the formed part under pressure to below T_g .

Slippage of graphite fiber during forming into part configurations has been shown to be dependent on the temperature of the material before, during, and after the application of forming loads. When the material is allowed to cool below the forming temperature (above T_g) during the forming process, the part configuration can be achieved but separation of layers of fiber occurs. The fiber must be allowed to slip within the thermoplastic matrix and then be reconsolidated at a temperature and pressure sufficiently high to repair separations.

Development activity also has demonstrated the capability of hot matched metal dies (Figure 5-2) to form complex shapes in graphite/thermoplastic material. Heating the dies above T_g forming the part, and then allowing the closed die set to cool below T_g requires a long turnaround cycle when auxiliary cooling is not employed. Production application of graphite/thermoplastic material requires forming parts in minutes to achieve maximum cost effectiveness.

Much energy is currently consumed to heat large masses of tooling used in many of the available processing methods for graphite/thermoplastic composite materials. Oven or autoclave heating cycles require hours for heating large tools to forming temperature (400 to 650 F). New methods of heating tooling require development. Highly efficient heating, radio frequency heating, and resistance heating of surface areas on large mass tools need to be evaluated as to their applicability to heating graphite/thermoplastic and their compatibility with low-cost tooling materials required for forming. Potential candidate tooling materials of plastic, concrete, electroform nickel, bulk graphite, and ceramic need to be evaluated to determine low-cost, highly efficient energy usage methods for forming graphite/thermoplastic matrix material. All of these materials with the exception of bulk graphite and ceramic have a significantly larger coefficient of thermal expansion than the graphite material that is being formed. Ideally, the

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Figure 5-1. Strake Tool

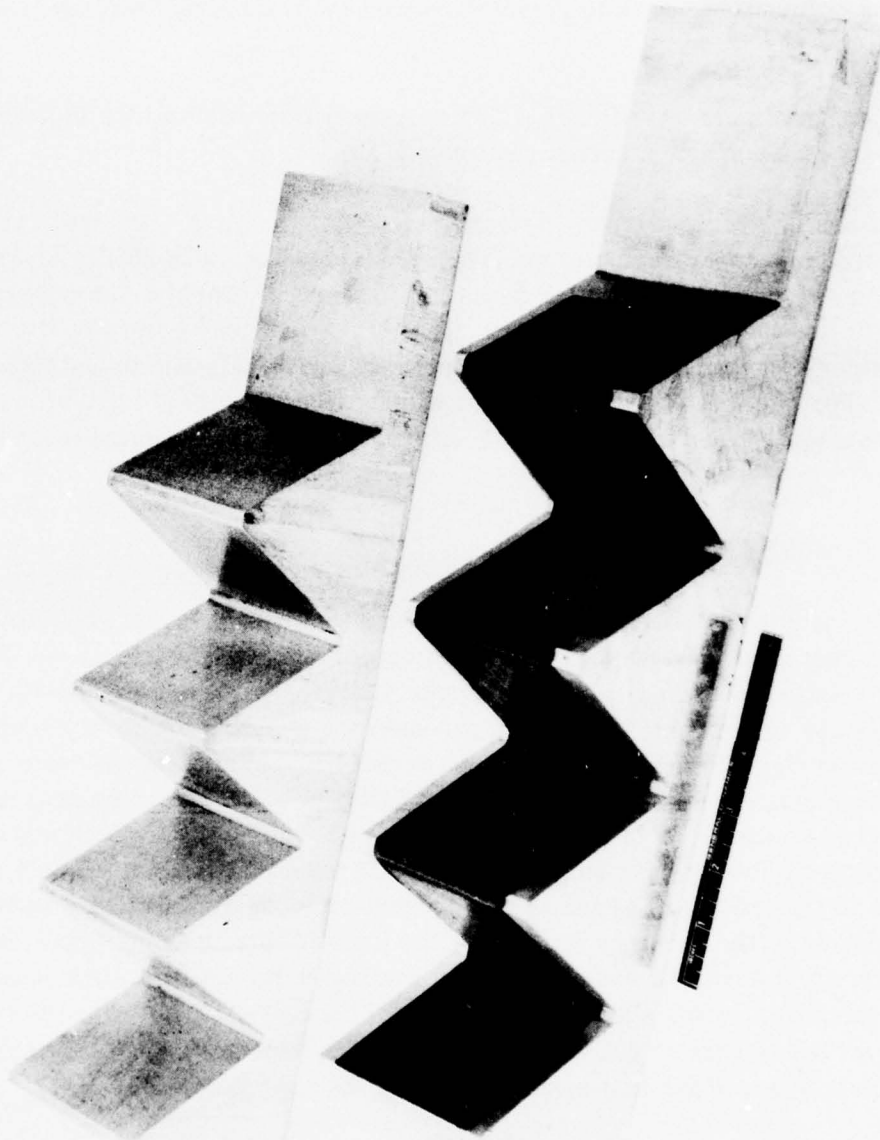


Figure 5-2. Corrugated A-S/Polysulfone Laminate
in Matched-Metal Die Set

design of the part to be formed should be such that the differential contraction forces the part out of the tool. A second approach, when the design cannot be adapted, is to design the tool (by separation plane or segmentation) so that the part is not locked into the tool. The only option left is to remove the part from the tool when the temperature is just below T_g .

Considering the minimum use of energy and minimum time in tool, the tool should be maintained at a constant temperature (just below T_g).

Each of these materials has already demonstrated its capability to be cast, plated, or machined to the tolerances required for aircraft structures. The ability to withstand the temperature and pressure requirements for forming of graphite/thermoplastic matrix structures, however, must be determined. In addition, compatibility for use with the highly efficient energy use heating methods previously mentioned must be determined. Parameters of temperature pressure and the critical application of each have been developed and new systems for heating and tooling must meet these requirements.

5.1 THERMOSETTING PLASTIC

Thermosetting plastic has been one of the standard tooling materials used for limited production curing of graphite/epoxy matrix advanced composite materials. Elevated temperature requirements for forming graphite/thermoplastic advanced composites has eliminated its use in the past. However, the use of new highly efficient energy heating systems that can heat only the material to be formed (e.g., microwave heating and radio frequency heating) now opens up the possibility of using this currently developed low-cost tooling material. The capability of plastic to withstand the temperature and force requirements to form graphite/thermoplastic needs to be studied and a determination made as to its acceptability for use in production tools for forming graphite/thermoplastic structures. The primary concern in the use of thermosetting plastic as a tooling material with microwave and radio frequency heating is its ability to withstand warm or hot surface temperature for a sufficient amount of time to not only form the thermoplastic composite part but to sustain surface temperatures in excess of 500F for periods of time to reconsolidate separations that occur during the forming operation.

5.2 MACHINED BULK GRAPHITE

Machined bulk graphite has been used at General Dynamics Convair for the autoclave curing of graphite/epoxy composites and for the forming of graphite/polysulfone. Figure 5-3 shows an internally heated and cooled die set used for forming a right angle in graphite/polysulfone. Figure 5-4 shows the formed part. This material has already demonstrated its compatibility with the graphite/polysulfone forming process. Significant potential problems, however, must be evaluated. Machining small tools and drilling short holes for the insertion of heating wires and cooling tubes is cost effective. However, as the part size increases, costs associated with the machining of complex

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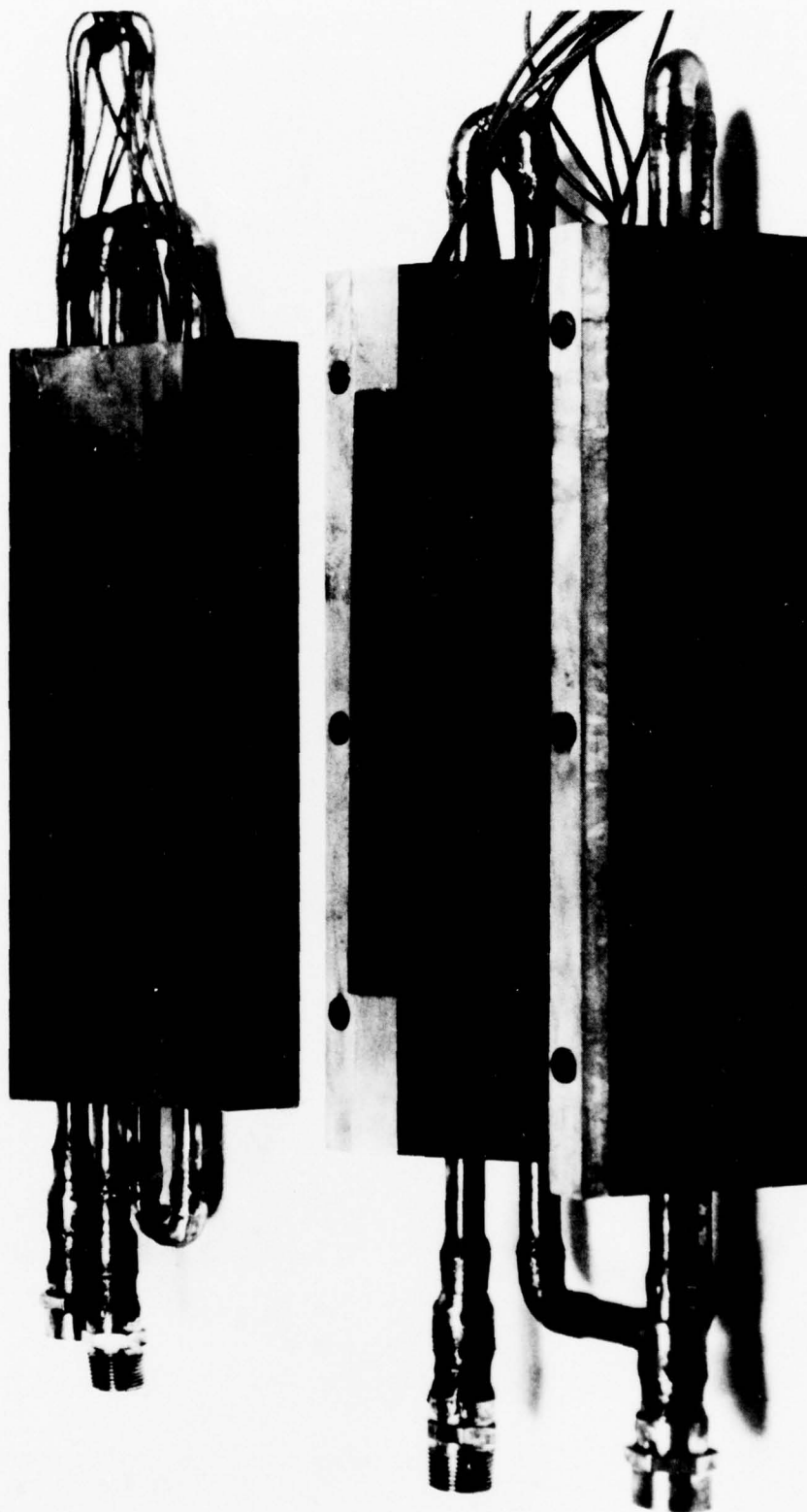


Figure 5-3. Bulk Graphite Tooling

NADC-77187-30



Figure 5-4. Part Formed on Machined Bulk Graphite Tooling

surfaces and the drilling of long holes may increase such that the tooling system will not be cost effective. In addition, insulating methods to be used between the machined graphite and the press platens used for forming must be identified. Heat transfer characteristics of the graphite are such that the entire tool is heated during the forming process. Cooling time cycles must also be determined to establish turnaround times that can be achieved in production. Excessive time in either heatup or cooldown of the tool are costly not only in manhours but in energy usage. To eliminate the requirement for internal heating, the compatibility of machined bulk graphite with microwave heating and radio frequency heating needs to be determined. Decreased cost both in tool fabrication and in forming cycle manhours could establish bulk graphite as a low-cost tooling material for use in forming graphite/polysulfone composite parts.

Convair recognizes that graphite tools can be electrically heated using the natural conductivity of the graphite. This process is limited to those tool shapes where a uniform current density within the tool is possible. The high energy demands and the hazards associated with an electrically hot tool, however, are factors that must be considered.

5.3 ELECTROFORMED NICKEL

The ability of electroformed molds to faithfully reproduce fine detail has been put to use for over half a century. One of the major attractions of electroformed molds is their ability to reproduce fine and accurate details (see Figure 5-5). The models for electroform molds can be of any of a wide range of material and include plastic rubber, wood, plastic, and most metals. Each of these materials is in common use in the aerospace industry and usually falls into the low-cost tooling area. Nickel electro-deposited to form electroform molds can be controlled in thickness from 0.020 inch to well over 0.5 inch. Its ability to reproduce part configuration along with the high strength of electroformed nickel (160 ksi tensile) makes it a prime candidate for use in forming dies required for forming graphite/polysulfone component parts. Areas of development are required, however, to identify and establish methods to support an electroformed nickel face used on a form tool for graphite/polysulfone and for determining efficient low-cost methods for heating and cooling the form tools to and from the elevated temperature required for forming.

5.4 CONCRETE

Concrete has a potential use in the fabrication of consolidation and postforming tools. Although most concrete is subjected to a range of temperatures no more severe than that imposed by weather, there are cases in which it is exposed to much higher temperatures. In investigations conducted at the Portland Cement Association Research and Development Laboratories on concrete exposed to temperatures in the 75 to 1500 F range, the following was concluded.

NADC-77187-30



Figure 5-5. Electroformed Inlet Leading Edge

- a. Concrete should not be exposed continuously to temperatures much above 500F when all surfaces will be exposed to heat.
- b. Sections with only one face subjected to heat can be exposed continuously to high temperatures up to 1000F.
- c. Continuous exposure to temperatures above 900 to 1000F may result in spalling of the concrete; greater resistance to spalling can be achieved with the use of crushed fire brick as an aggregate.

Previous use of internally heated and cooled concrete tools used in the curing of Kevlar-29 at Hughes Helicopter at temperatures up to 328F have proven to be low in cost and set a precedent for its use as a tooling material. Significant energy savings were also achieved by eliminating the use of continuous-operation curing ovens.

5.5 METAL

Machined matched metal tools have been used for postforming graphite/polysulfone and in most cases proven to be expensive and not energy efficient. The use of metal tools for postforming parts with minor contours using vacuum bags and autoclave or vacuum pressure as normally used in the curing of graphite/epoxy has been limited because reliable vacuum bag materials and sealants that can withstand temperatures above 500F have not been available. Convair has been working with Airtech International Inc. to develop a vacuum bagging material and sealant for use at temperatures up to 800F. At present, a bagging material, Vacalloy and sealant AT500, good to temperatures up to 700F, has been developed.

Machined metal tools of thin cross-section can be used for forming graphite polysulfone. The laminate is bagged to the surface of the tool using vacuum or autoclave pressure, depending upon the amount of contour to be formed. This process uses less energy than that previously used for curing graphite/epoxies.

5.6 CERAMIC

Ceramic tooling used in postforming graphite/polysulfone component parts has, to a limited degree, proven to be successful. Ceramic tools internally heated and cooled and plain ceramic tools have been developed and used at Convair under both Air Force and Navy contracts. Although the tooling produced satisfactory parts, problems of sealing the surface of the ceramic at elevated temperatures to eliminate sticking to the porous ceramic and the high cost of tool fabrication were not solved. These problems have been investigated and new ceramic systems identified that potentially can solve the problem of sealing the ceramic and reducing fabrication cost. A new lower cost ceramic compound has been developed by Convair with the assistance of Aerospex Corp. It has a coefficient of expansion that approaches the coefficient of expansion of electroformed nickel. Temperature cycle tests up to 800F on the new ceramic cast into an electroform

NADC-77187-30

nickel face (Figure 5-6) have shown no separation between the nickel and ceramic. The combination of nickel faces on ceramic tooling when totally developed will not only solve the problem of graphite/polysulfone sticking to ceramic but gives the tooling the same advantages as a metal tool for using currently developed release agents. In addition to addressing the problem of sealing ceramic, Convair has investigated methods by which ceramic tooling cost can be reduced. Although large cast tools of ceramic are expensive, ceramic face tools that take advantage of energy efficient resistance heating with a back-up structure of cast concrete lower fabrication cost over 40 percent.

NADC-77187-30



Figure 5-6. Ceramic/Nickel Compatibility Samples

SECTION 6

DEMONSTRATION ARTICLE TOOLING SELECTION

The demonstration article selected for the program was the ammunition bay door for the F-16 aircraft. After evaluation of the door design, facility availability, and cost tradeoffs, it was determined to use aluminum matched-metal dies for the forming of the detail parts. The tools, when used for preforming, were heated in an air oven. When the tools are used for the final forming of the detail part, they were heated by an electric blanket located between the faces of the dies.

Figures 6-1 through 6-4 show the design of the tools to be used for forming the door skin, door doubler, and channel. The tool used for forming the door skin and door doubler was also used for primary bonding the two detail parts together. This operation was accomplished by placing both detail parts in the tool during the final forming operation. The reconsolidation process that takes place during forming created the bond between the detail parts.

The completed tools to be used for forming the skin, skin doubler, channel, and primary bonding the skin doubler to the skin are shown in Figures 6-5 through 6-7.

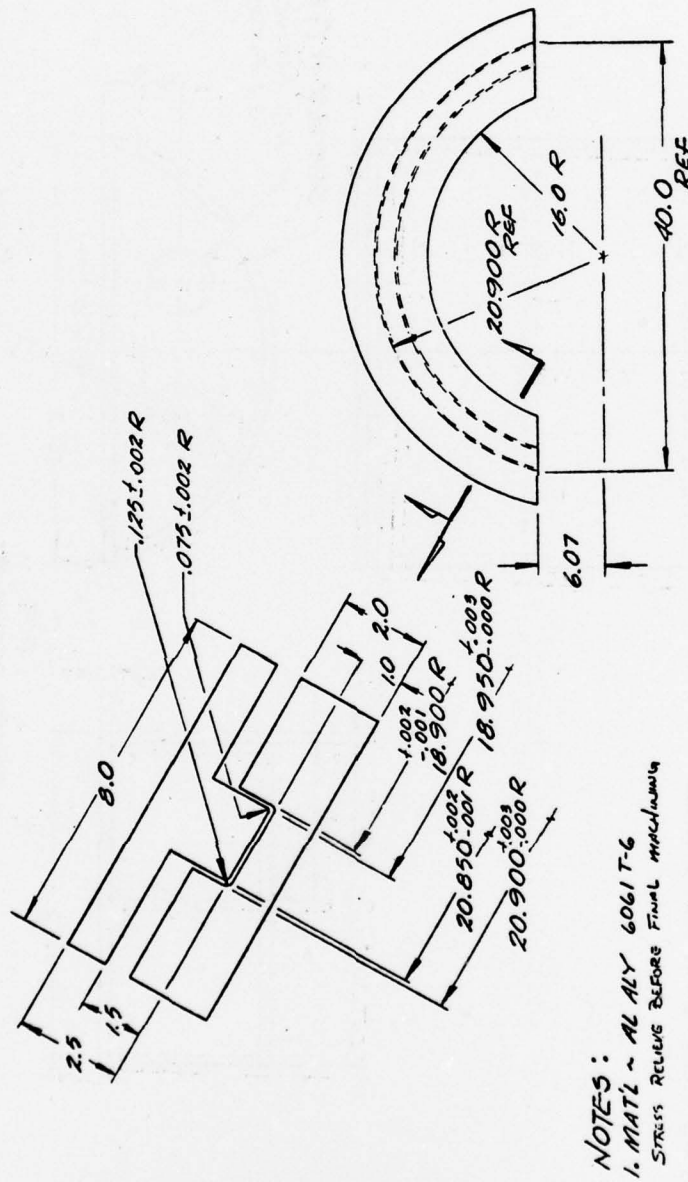


Figure 6-1. Channel Form Tool - 72C0581-103

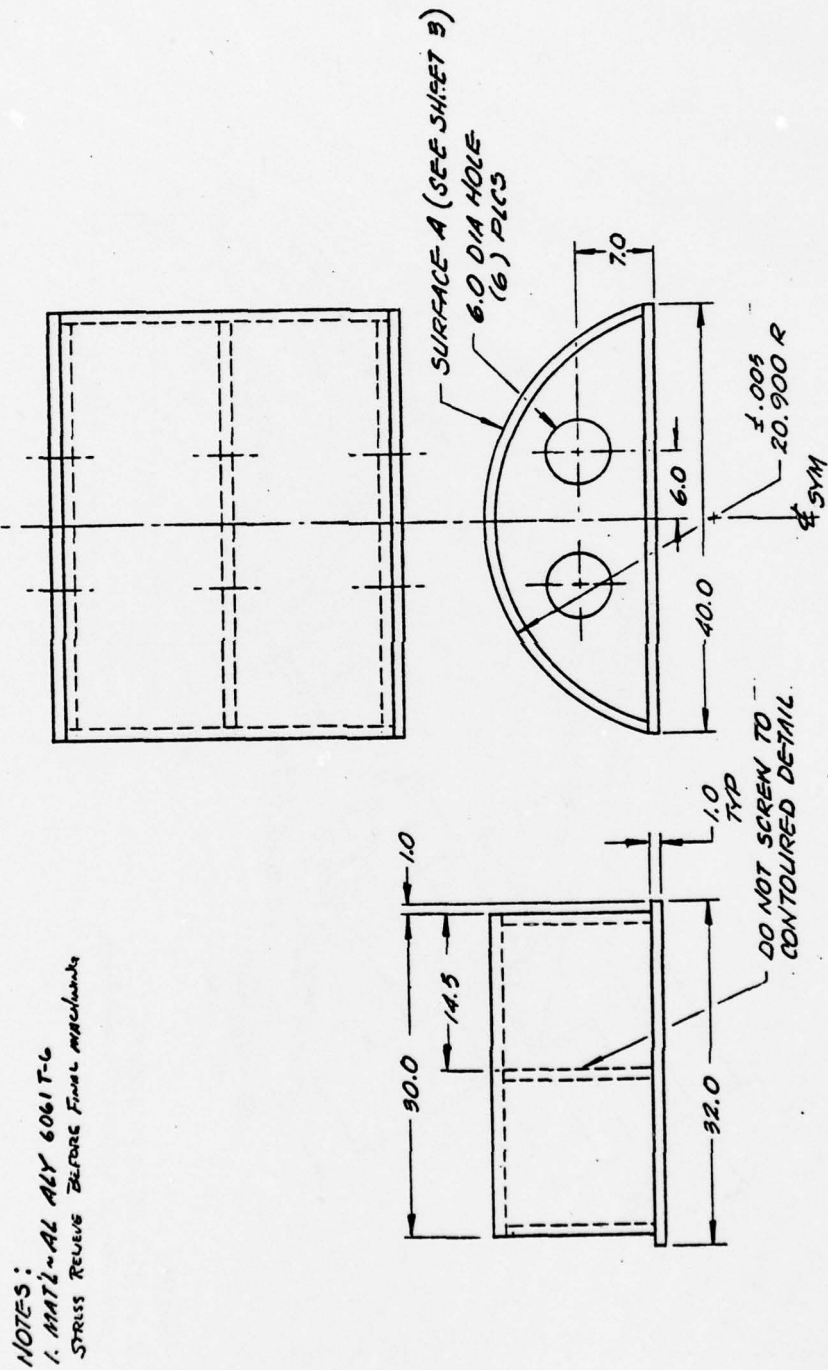


Figure 6-2. Thermoplastic Form Tool ~ Skin - 72C0581-101A

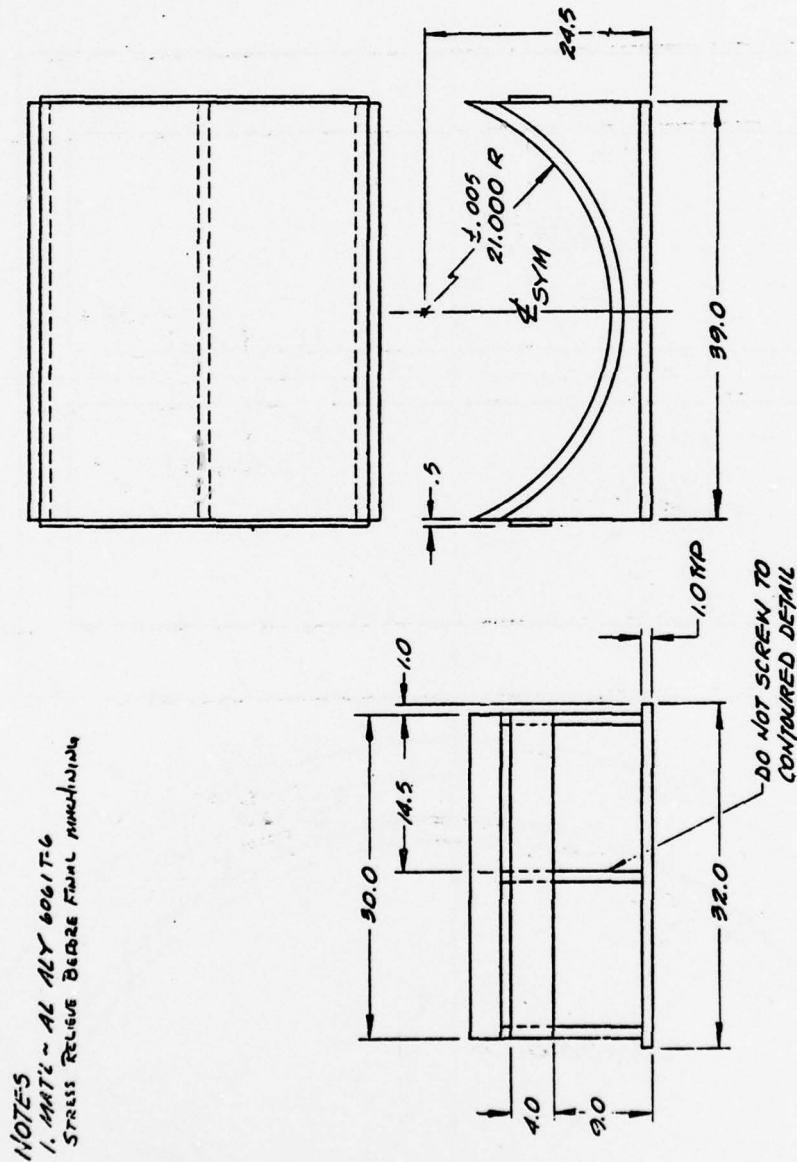


Figure 6-3. Thermoplastic Form Tool ~ Skin - 72C0581-101B

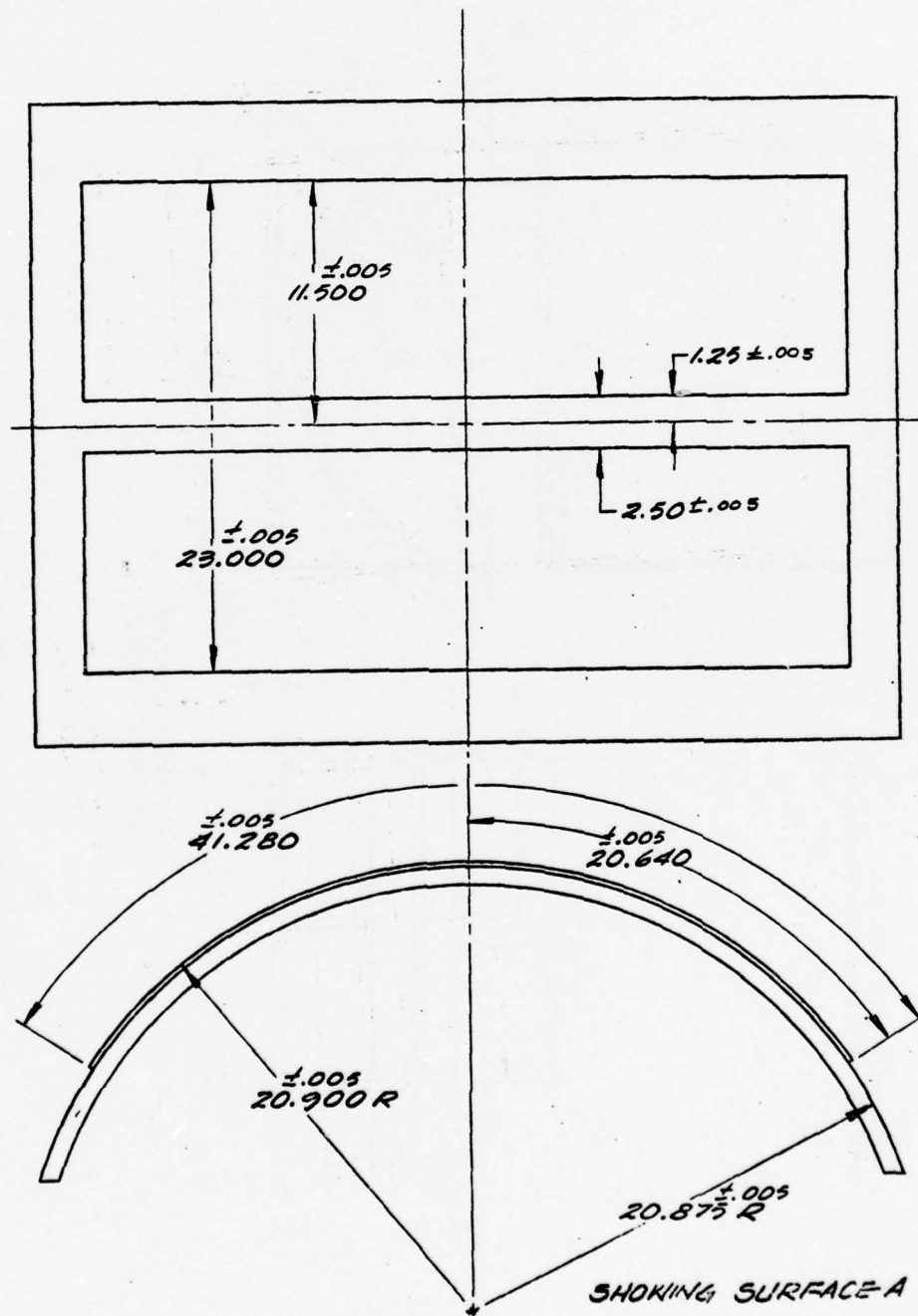


Figure 6-4. Thermoplastic Form Tool ~ Skin 72C0581-101A

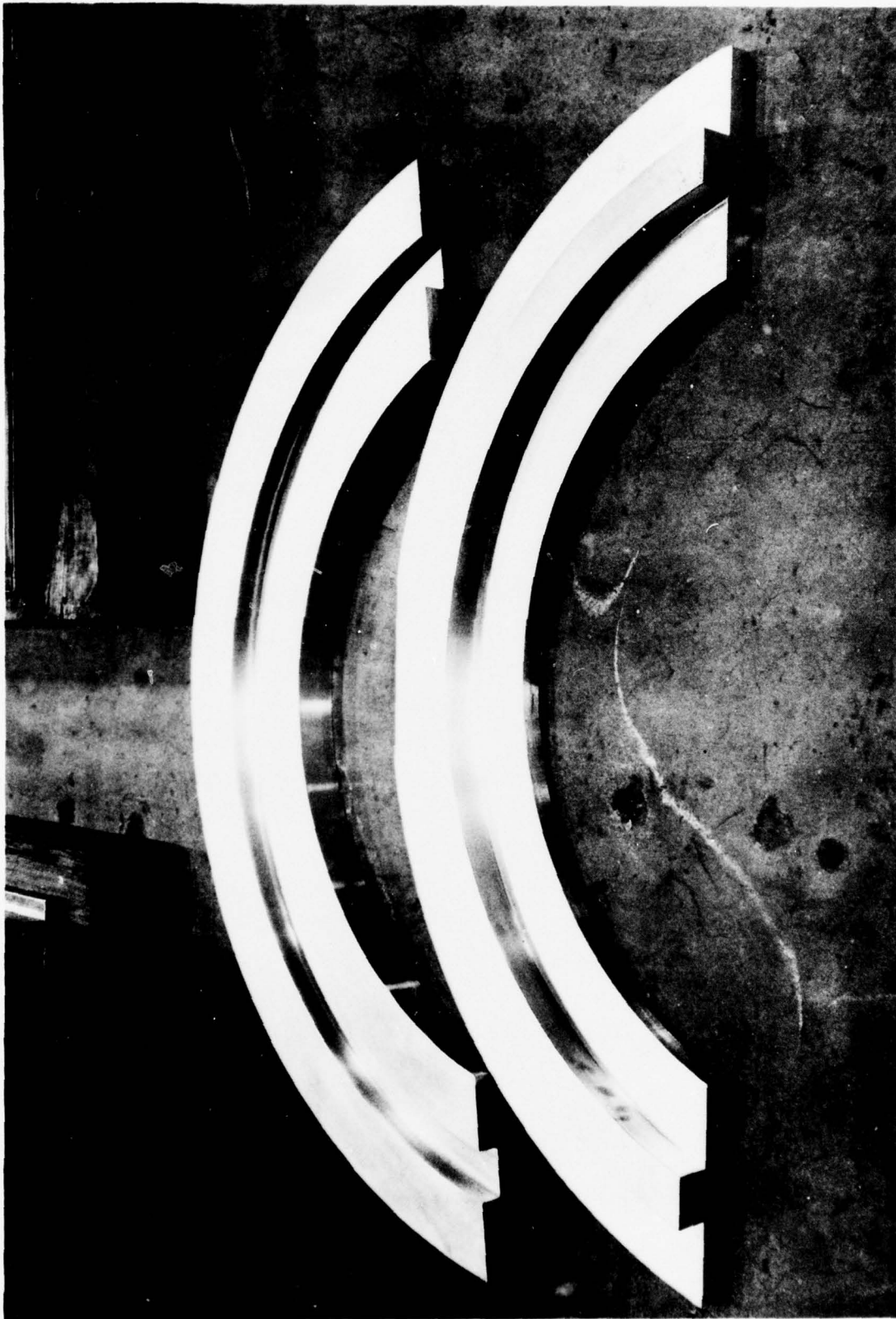


Figure 6-5. Curve Channel Form Tool

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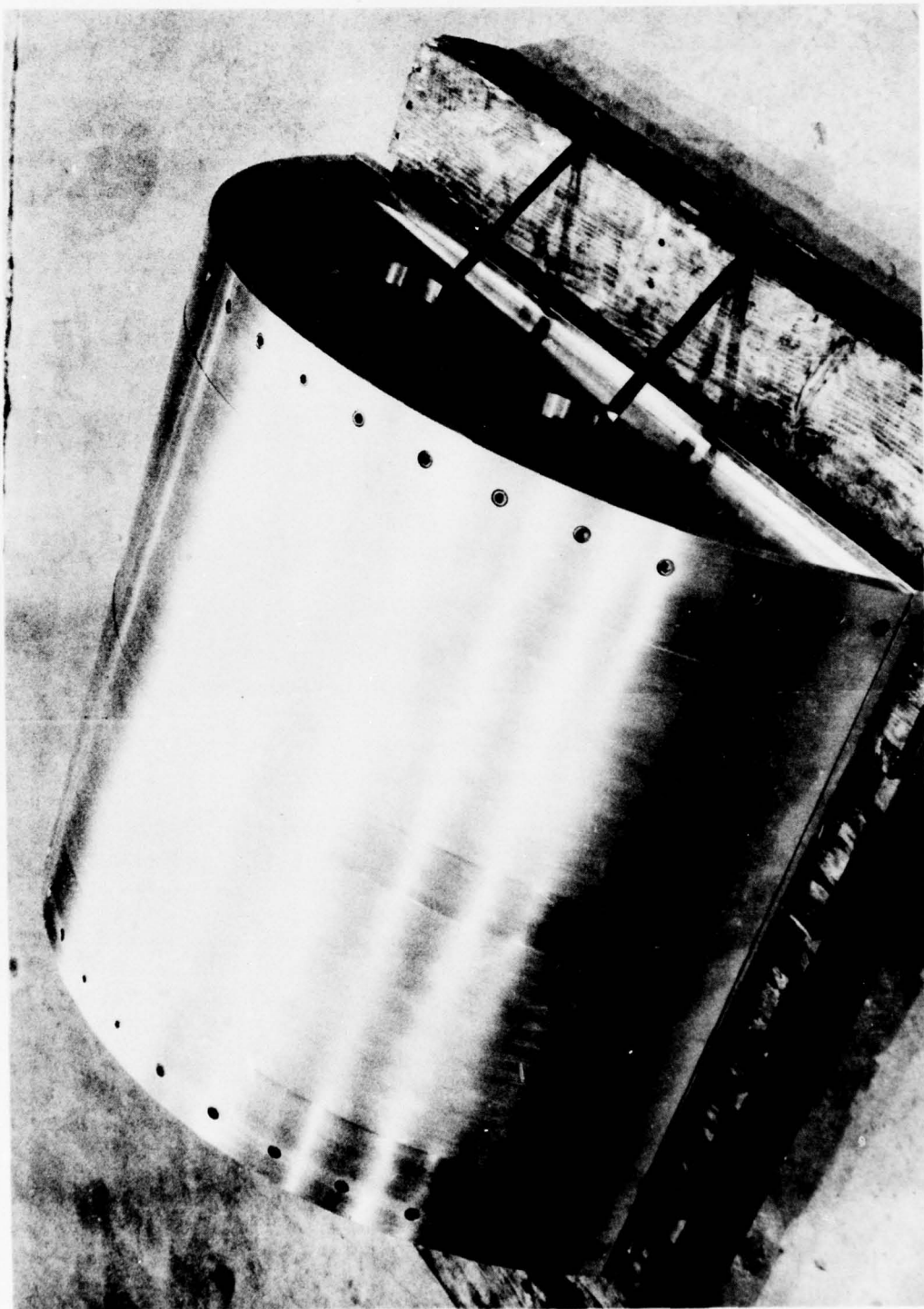


Figure 6-6. Ammunition Bay Door Male Skin Tool

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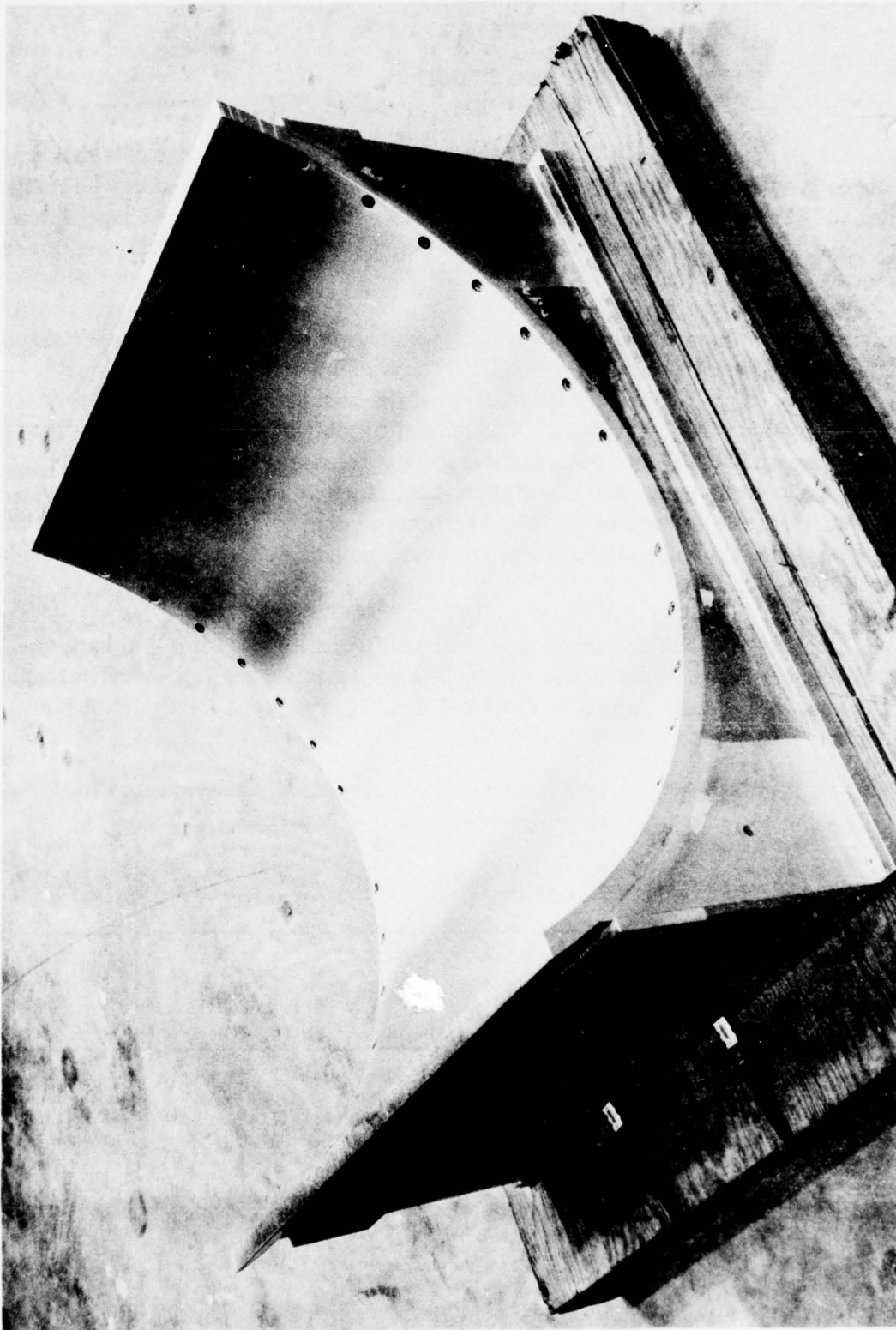


Figure 6-7. Ammunition Bay Door Female Skin Tool

SECTION 7

JOINING STUDIES

Joining by two techniques was evaluated as part of the program. The use of a thermoplastic matrix in advanced, fiber-reinforced composite offered a new and unique method of joining in addition to the standard methods such as adhesive bonding and mechanical fastening. Joints consisting of ultrasonic spotwelds, both single and double, and mechanical fasteners were evaluated.

The static strength of the spotwelded specimens was highly variable and the specimens displayed a very low bending or peel strength. The welds represented the highest strengths available using the ultrasonic welder and the basic material used for the fabrication of the ammunition bay door. The lack of bending strength was due to the small amount of resin involved in the weld and the low tensile strength of the basic resin. In our opinion the welds had insufficient peel strength to make them feasible for any practical use in the structure. The addition of resin to the outer surface would increase the weld tensile and peel strength; however, no additional testing was conducted on the remaining specimens.

Figures 7-1 through 7-3 show the three specimen configurations. Table 7-1 summarizes the Type A specimen dimensions. Table 7-2 summarizes the lap shear strength of the single spotweld tests. Tables 7-3 and 7-4 give the strengths for the multiple spot and bolted specimens.

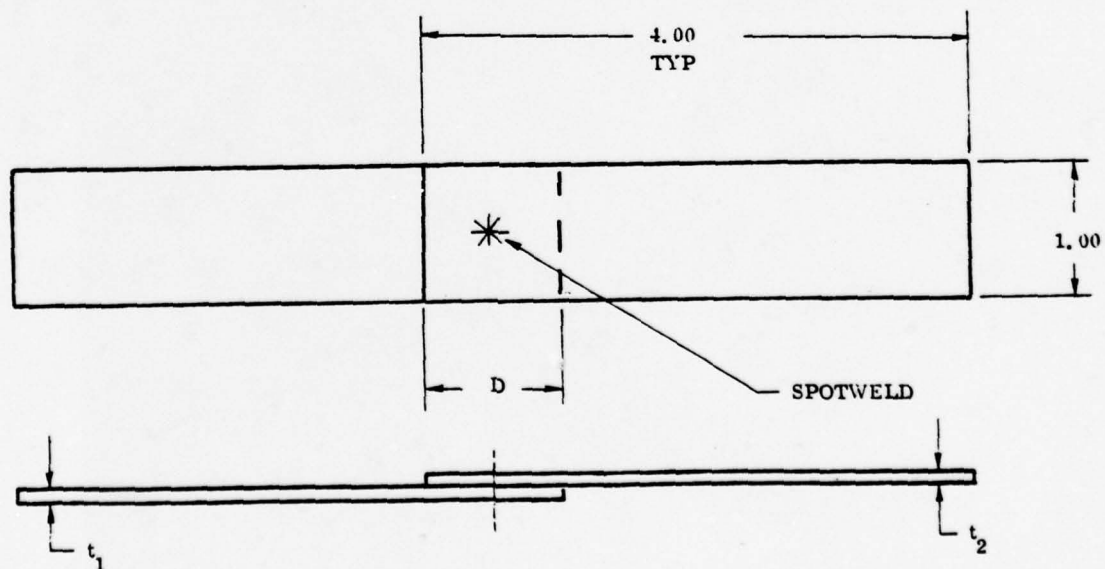


Figure 7-1. Single Spotweld Specimen, Type A

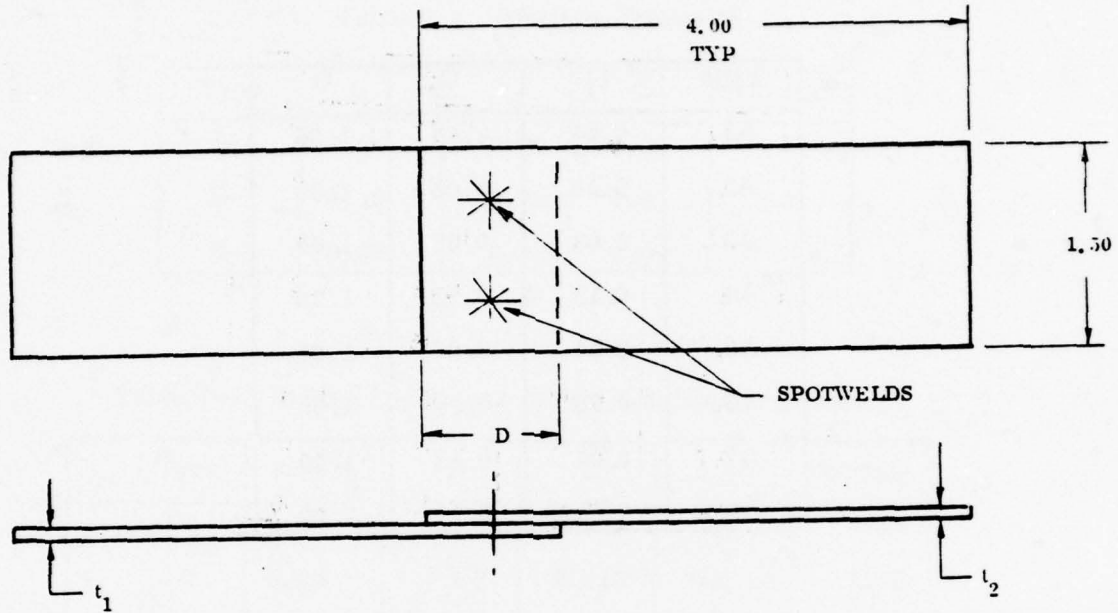


Figure 7-2. Double Spotweld Specimen, Type B

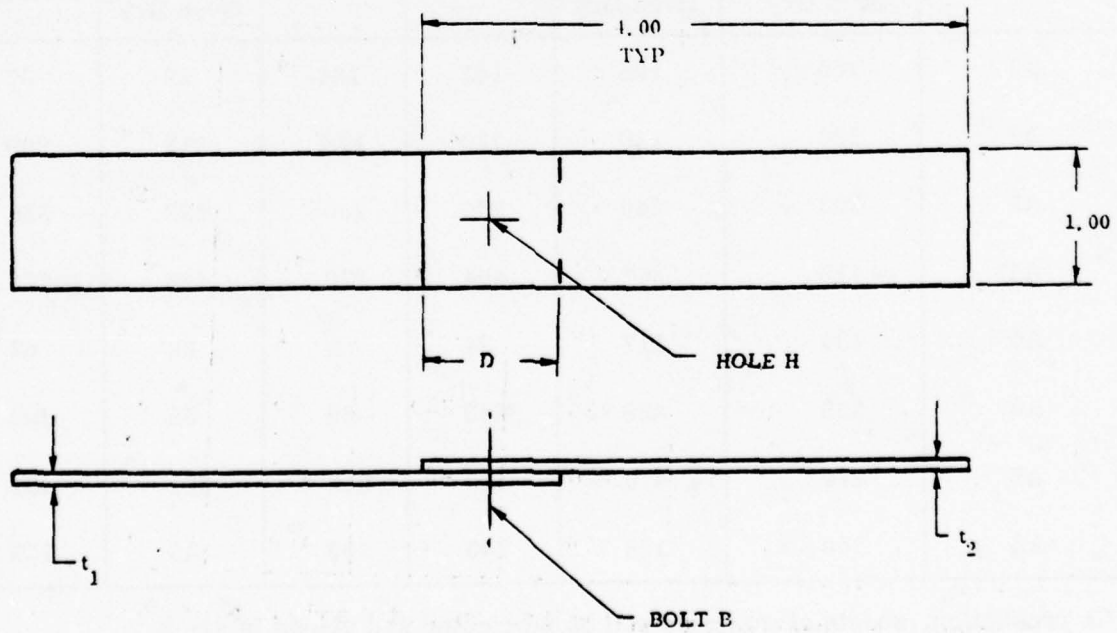


Figure 7-3. Bolted Joint Specimen, Type D

Table 7-1. Specimen Dimensions

Type	t ₁	t ₂	D
A1	0.04	0.04	1.00
A2	0.06	0.06	1.00
A3	0.08	0.08	1.00
A4	0.12	0.12	1.25
A5	0.04	0.06	1.00
A6	0.06	0.08	1.00
A7	0.08	0.12	1.00
A8	0.04	0.12	1.00

Table 7-2. Lap Shear Strength (pounds)

Specimen	Test 1 Oven Dry*	Test 2 Oven Dry*	Test 3	Test 4	Test 5 Oven Dry*	Average
A1	106	105	101	134	37	97
A2	220	130	210	148	313	209
A3	202	240	380	430	429	336
A4	413	267	404	320	448	370
A5	134	117	34	1	22	62
A6	553	438	350	65	52	292
A7	470	476	450	518	391	461
A8	280	178	145	100	43	149

*In production, sheets of material will be fabricated and placed in stack.

These specimens (oven dry) were dried prior to welding to determine if any moisture picked up during storage would have an effect on the strength of the weld. The results did not indicate any effect.

Table 7-3. Multiple Spotwelds

Type	t_1	t_2	D	Strength
B-1	0.04	0.04	1.00	238
B-2	0.12	0.12	1.25	542
B-3	0.06	0.08	1.00	Broke

Table 7-4. Bolted Specimens (Single Mechanical Fastener)

Type	t_1 & t_2	D	H	B	Strength
D1	0.04	1.00	0.190	No. 10	844
D2	0.06	1.00	0.190	No. 10	1500
D3	0.08	1.00	0.190	No. 10	1920
D4	0.12	1.00	0.250	1/4 in.	3200

SECTION 8

DEMONSTRATION ARTICLE FABRICATION

8.1 INTRODUCTION

Forming of all detail parts to be used in the ammunition bay door was planned to be accomplished using matched metal dies. The dies would be placed in a Williams-White 600-ton hydraulic press and electrically heated (using a blanket) to 550F. The blanket would then be removed and a flat consolidated sheet of graphite/thermoplastic placed between the dies. The sheet of graphite/thermoplastic would then be heat soaked for five minutes. At completion of the heat soak, a forming pressure of 200 psi would be applied. The formed part and tool would then be force air cooled to 325F before releasing the pressure and removing the part. The skin and skin doubler were planned to be formed in a single operation that would also create a primary bond between the two parts — the bend being accomplished due to the flow of the thermoplastic resin during the forming operation.

8.2 CURVED CHANNEL FORMING

Forming of the curved channels for the ammunition bay door was accomplished using the matched aluminum die set shown in Figure 6-5 in Section 6. The dies were given six coats of Freekote 33 release agent and located in the 600-ton, Williams-White press. A heating blanket was placed between the die halves, and two thermocouples were located in the die and in the punch. Insulation was then placed around the tool to minimize heat loss. Heat was then applied and the tool raised to a temperature of 550F. After temperature was reached the heating blanket was removed and a flat sheet of graphite/thermoplastic was placed between the die and punch and allowed to heat soak for five minutes. The insulation around the tool was then removed and a forming pressure of 200 psi applied to the part. The tool and part were then force air cooled to 325F while the 200 psi forming pressure was maintained on the part. When the temperature of 325F was reached, the forming pressure was released and the part removed.

The part was removed while hot due to the difference in thermal coefficient of expansion between the aluminum tool and graphite/thermoplastic formed channel. Even at a temperature of 325F, the formed channel had to be pried out of the female die. There was no problem with removal of the male punch. Completed formed curved channels are shown in Figure 8-1.

8.3 SKIN AND SKIN DOUBLER FORMING

To form the skin and skin doubler it was first necessary to preform the detail parts. This operation was necessary because there was insufficient open height in the

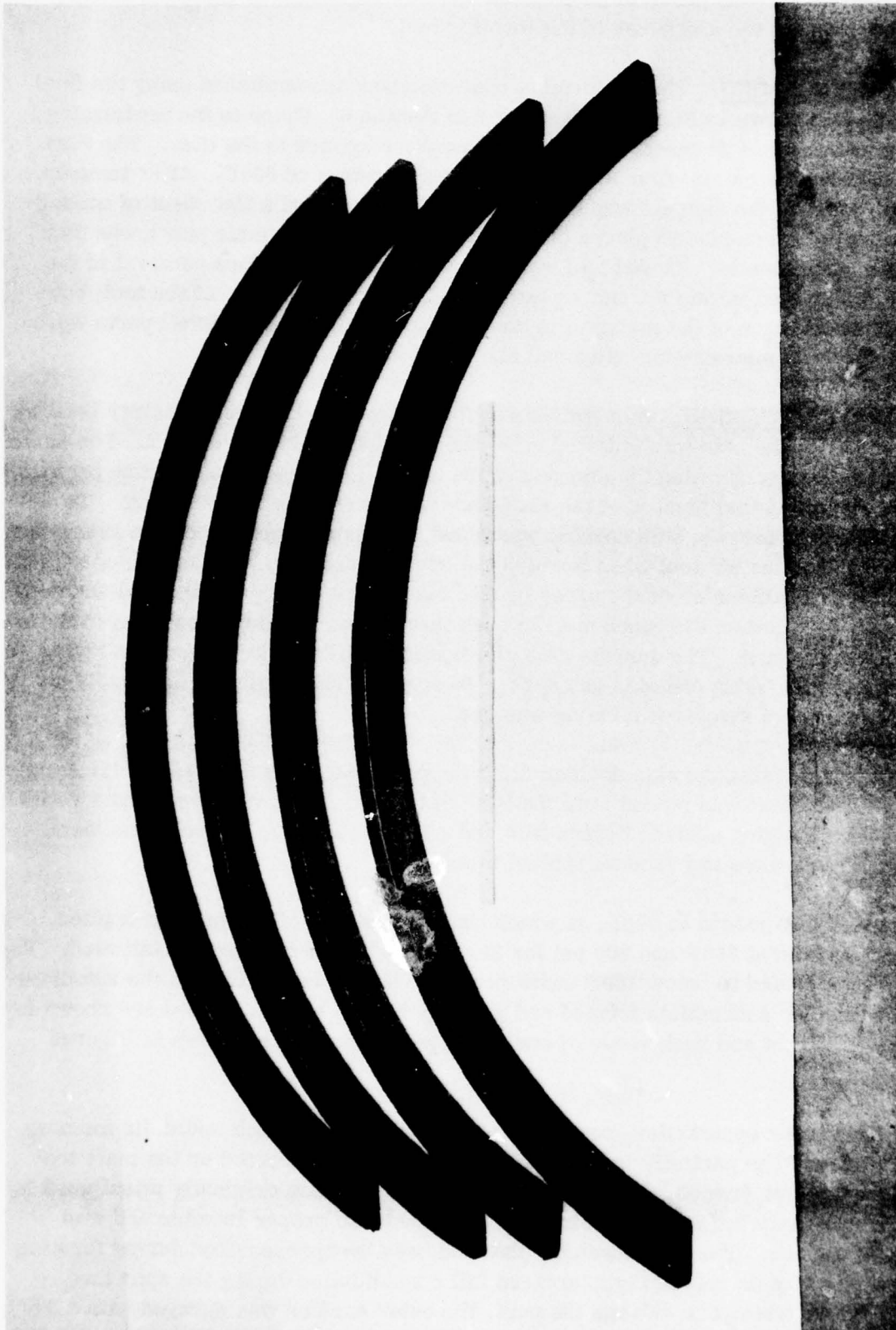


Figure 8-1. Formed Curved Channels

Williams-White 600-ton press to place a flat sheet of consolidated graphite/thermoplastic between the die and punch of the forming tool.

8.3.1 PREFORMING. The preforming operation was accomplished using the final forming die set shown in Figures 6-6 and 6-7 in Section 6. Prior to the preforming operation six coats of Freekote 33 release agent were applied to the dies. The dies were then placed in an air oven and raised to a temperature of 600F. After temperature was reached, the dies set was removed from the oven and a flat sheet of consolidated graphite/thermoplastic placed over the female half. The male punch was then lowered into the female. Closed tool was then cooled to 300F before removal of the part. Parts formed in this manner achieved the basic configuration of the tool; however, reconsolidation of the material is not accomplished. Twelve detail parts were preformed in this manner—six skins and six skin doublers.

8.3.2 FINAL FORMING. Skin and skin doubler forming along with primary bonding of the doubler to the skin was initiated using the aluminum matched die set. The same procedures used for forming the channels were used. However, when loading preforms into the hot dies, misalignment of the skin doubler occurred on the first part. To eliminate the problem the skin doubler was taped into proper location on the skin before being placed into the hot tool when forming the second part. During forming of the second part, a malfunction of the press caused overpressurization of the tool and damaged alignment between the punch and die such that proper forming pressures could not be applied to the part. The damage also eliminated further use of the matched tools for forming of the skins and skin doublers. To accomplish forming of the parts, an alternate method of autoclave forming was used.

For autoclave forming the skin doubler and skin were placed on the male tool. A stainless steel caul sheet was placed over the back of the skin, then vent cloth and a vacuum bag. Vacuum bagging utilized Kapton film and AT-800 sealant. The tool was then placed in an autoclave and vacuum applied to the part.

The part was then raised to 600F, at which time a pressure of 200 psi was applied. The part was held at 600F and 200 psi for 30 minutes before cooling was initiated. The part was then cooled to below 300F under pressure before removal from the autoclave. Skin/skin doubler assemblies formed and primary bonded by this method are shown in Figure 8-2. Front and back views of one of the parts formed are shown in Figures 8-3 and 8-4.

After forming four assemblies, rework of parts damaged in match metal die forming was attempted. The partially formed skin assemblies were located on the male tool and were autoclave formed. The skin assembly that had been originally misaligned in the tool during matched metal forming was reformed into proper location and was acceptable for use. The skin assembly that had been overpressurized during forming had insufficient resin remaining to achieve full consolidation during the autoclave forming. In an attempt to salvage the part, the outer surface was sprayed with a 5%

NADC-77187-30



Figure 8-2. Four Formed Skins

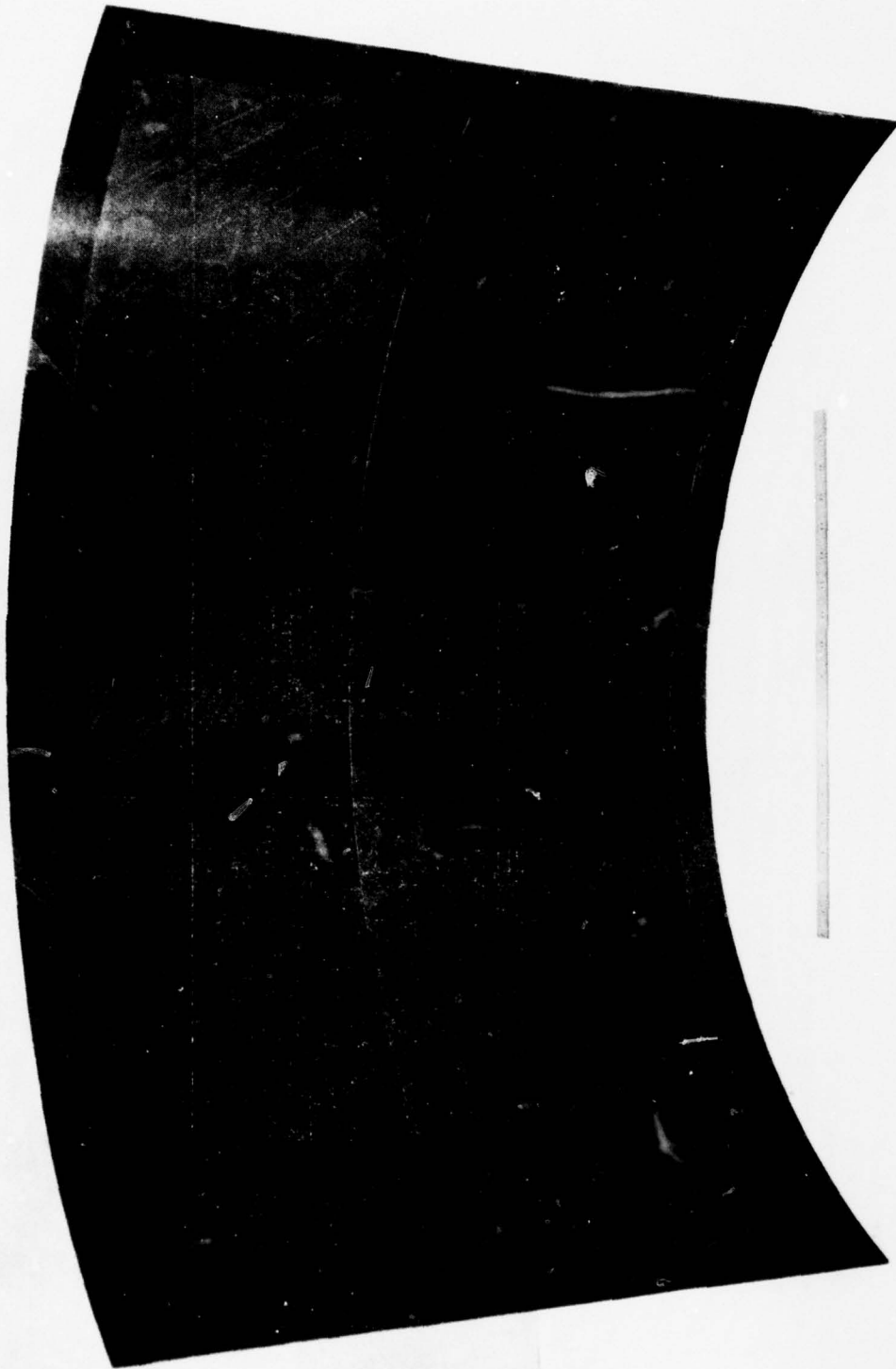


Figure 8-3. Front of Formed Skin

NADC-77187-30



Figure 8-4. Back of Formed Skin

solution of polysulfone and methylene chloride, and then reformed in the autoclave. Consolidation of the part was improved, but not within acceptable limits. Further rework of the assembly was not attempted.

8.4 SKIN/SKIN DOUBLER ASSEMBLY

Trimming of the skin/skin liner assembly was accomplished by laying the part out on the bench and then using a band saw to trim the part to final dimension. Filing was then used to smooth the edges and bring the parts to final dimension.

8.5 BEAM TRIMMING

Trimming of the center beams was accomplished using a Boko pattern mill. The Boko pattern mill is set to the dimensions required and the part is passed across the cutter. Filing was then used to smooth the edges of the parts.

8.6 DOOR ASSEMBLY

Assembly of the ammunition bay door was accomplished by adhesive bonding the center curved channel to the skin/skin doubler. The female form tool was used to maintain the part contour and the curved channel was located. EA9309 adhesive was then placed on the detail parts. The parts were then clamped in place and allowed to cure at room temperature for 24 hours before being removed from the tool. The completed ammunition bay door assembly is shown in Figures 8-5 and 8-6.

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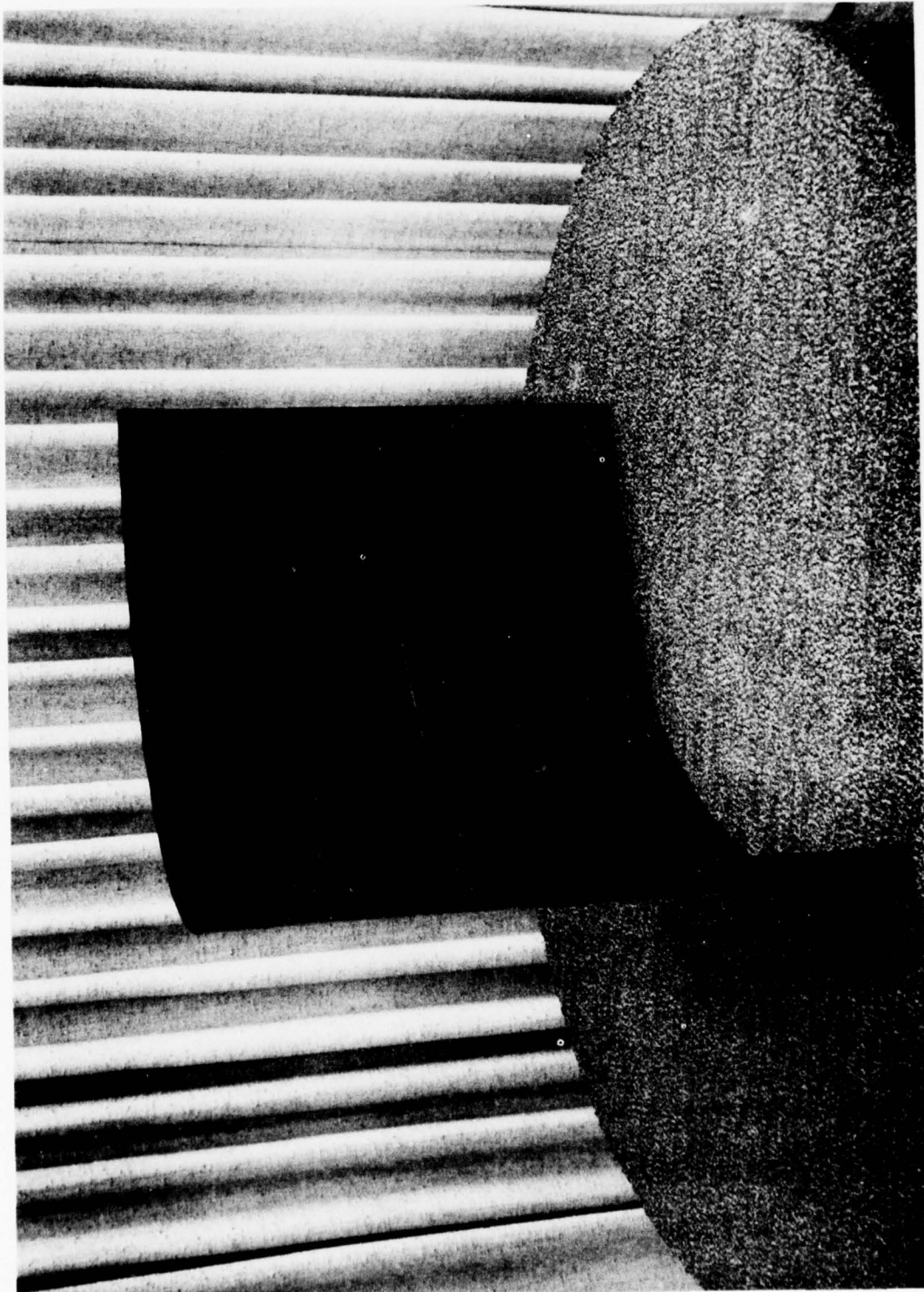


Figure 8-5. Completed Ammunition Bay Door Assembly, Front

NADC-77187-30



Figure 8-6. Completed Ammunition Bay Door Assembly, Back

SECTION 9

ECONOMIC ANALYSIS

The cost comparison was made between an all-metal door and a door fabricated from graphite/thermoplastic (G/TP). The following ground rules and data were used in preparing the estimate.

- a. Only fabrication recurring costs are shown.
- b. Costs are in constant 1976 dollars.
- c. Costs are based on producing 100 units in four lots.
- d. Profit is not included.
- e. Press consolidation for G/TP (heated and cooled plate).
- f. Press forming for G/TP (heated and cooled dies).
- g. G/TP material is layed up using a machine.
- h. All G/TP material is fabricated in one lot (same as buying all sheet metal at one time).
- i. All G/TP cloth is purchased in 26-inch-wide rolls ($\pm 45^\circ$) for skins and 35-inch-wide for channels.

9.1 METAL DOOR

9.1.1 DESCRIPTION. The door consists of a single contour skin riveted to a single frame. The door is 26 inches wide by 40 inches long and is fabricated from aluminum alloy 2024.

9.1.2 MANUFACTURING FACILITIES. All manufacturing facilities are available.

9.1.3 TOOLING

Skin:	Check form to check skin contour Cutting pattern to establish etch areas Trim shell for final trim
Frame:	True trace blanking dies Hydropress form Trim template
Assembly:	Assembly fixture for use with automatic rivet machine.

9.1.4 MANUFACTURING SEQUENCE

Skin: Roll form
Mask
Etch double pattern
Final trim
Clean up and sell

Frame: Blank
Form (hydropress)
Heat treat and straighten
Trim
Clean and apply finish

Assembly: Locate skin and frame in assembly fixture
Install rivets (machine)
Clean and apply finish

9.1.5 AVERAGE COST OF METAL DOOR

Material	\$ 14
Fabrication and assembly	\$ 76
Quality control	<u>\$ 11</u>
Total	\$101

9.2 COMPOSITE DOOR

9.2.1 DESCRIPTION. Same as metal door except frame is bonded to skin in place of being riveted.

9.2.2 MANUFACTURING FACILITIES. Presses for consolidation and forming must be purchased.

9.2.3 TOOLING

Skin: Trim template for fluid jet cutter (flat)

Doubler: Trim template for fluid jet cutter (flat)

Skin/
Doubler

Assembly: Matched metal dies (heated and cooled to reduce forming cycle time)
Trim template for fluid cutter

Frame: Trim template for fluid jet cutter (flat)
 Matched metal dies (heated and cooled)
 Trim template for fluid jet cutter (final)

Assembly: Bond tool (to hold part during cure)

9.2.4 MANUFACTURING SEQUENCE

Skin: Lay up stack
 Consolidate
 Trim

Doubler: Lay up stock
 Consolidate
 Trim

Skin/
 Doubler Pre-heat skin and doubler
 Lay doubler on die

Sub- Lay skin on die

Assembly: Lay skin on die
 Form (also bonds skin to doubler)
 Trim

Frame: Lay up stack
 Consolidate
 Trim
 Form
 Trim

Assembly: Locate skin in assembly fixture
 Apply adhesive
 Bond frame to skin

9.2.5 AVERAGE COST OF COMPOSITE DOOR.

Material	\$261
Fabrication and assembly	\$ 74
Quality control	<u>\$ 10</u>
Total	\$345

SECTION 10
CONCLUSIONS AND RECOMMENDATIONS

General

The objective of this program was to extend the developments already accomplished and in work in graphite/thermoplastic materials to the general area of stiffened, curved fuselage structural panels for advanced Navy Aircraft. Convair believes that the objective of this program has been achieved.

Before proposing the use of any composite material, the resin softening temperature, and the temperature where the resin and/or fiber begin to breakdown, should be determined.

Consolidation

Summarizing the work accomplished on consolidation reveals the rather broad band for consolidating polysulfone composites (Ref. Figure 4-10). As long as the pressure is high (~300 PSI), temperatures as low as 500F can be used. Where the temperature is high (675F), pressures as low as 50 PSI may be used.

Based on the data available at this time, there are only two proven methods for consolidating stock (Press and Autoclave). It is possible that a series of rolls could be used to consolidate the stock. This rolling method would probably be the most economical, but would probably not produce optimum mechanical properties.

It is recommended that further studies be made to establish the minimum dwell time required to product high quality consolidation (Ref. Figure 4-9). If the time can be reduced, the cost to fabricate and facilitate can also be reduced.

Tooling

The selection of the tooling method and tooling material must be based on the product (shape and size) to be fabricated, the availability of facilities (presses, autoclaves, etc.) and the quantity of the products to be produced. Special attention should be given to avoid problems which result from the difference in thermal expansion/contraction between the tool material and the material of the part being formed. It should be noted that if the tools are kept at a constant temperature then the effect of thermal expansion is minimized.

It is recommended that further studies be made on the use of ceramics for tools. Cracking of the material is still a problem that needs to be solved. The castability of ceramics is very useful in making tools that have complex contours.

CONCLUSIONS AND RECOMMENDATIONS (Cont'd.)

Forming

During this study the consolidated stock was pre-formed between the dies (forming temperature is unknown). Final forming was done at 600°F with 200 PSI pressure and held for 30 minutes. (Material was held to die by vacuum.)

It is recommended that further work be done to study effect on properties of material heated to forming temperature in air, die heated to just below softening temperature, then formed. The minimum time that pressure must be held should be established.

Joining

It is recommended that present designs continue to join thermoplastic material with adhesives or mechanical fasteners or a combination of both. The use of ultrasonic welds has not been proven as a reliable joining method. A program specifically planned to develop this joining method would be required before the welding could be used in actual structure.

Cost

This door is a simple (inexpensive) part to fabricate in either aluminum or graphite/thermoplastic (G/TP). A part that would require more expensive forming operation would show the cost advantage of using the composite material. In order to show a cost advantage with the use of G/TP, the labor cost must be reduced an amount that exceeds the greater cost of the material.

Many designs lend themselves to the use of thermoplastic material. The two most important factors which influence the cost of a thermoplastic (or any composite) part are: 1) part is designed to be made from thermoplastic right from the start and 2) material costs must come down (this will be possible if graphite fiber is used in large amounts in this automotive industry).

Material

In order to minimize the cost of material and the cost to facilitate, it is recommended that material supplier (pre-preger) should be encouraged to facilitate to the extent necessary to be able to supply broad goods, made up of tape or cloth, at the required orientation and to the required thickness to the users.

APPENDIX A

COMPOSITE AMMUNITION BAY DOOR ANALYSIS

Section Properties: Mid-Ring

The selection properties were obtained by use of a computer and the results are:

$$\bar{y} = 0.857 \text{ in.} \quad A = 0.175 \text{ in.}^2 \quad I_x = 0.10478 \text{ in.}^4$$

Local Shear Buckling Between Rings

(See Reference 1, Figure 49c.)

$$a = 45 \text{ in.}$$

$$b = 13 \text{ in.}$$

$$r = 21 \text{ in.}$$

$$t = 0.072 \text{ in.}$$

$$Z_b = (b^2/rt)(1-\nu^2)^{1/2}$$

$$= (13^2/21 \times 0.072)(1-0.33^2)^{1/2}$$

$$= 112 \times 94$$

$$= 106$$

$$a/b = 45/13 = 3.46$$

$$k_s = 27$$

$$\tau_{cr} = \frac{k_s \pi^2 E}{12(1-\gamma^2)} \left(\frac{t}{b} \right)^2$$

$$= \frac{27 \pi^2 \times 10.5 \times 10^6}{12(1-0.33^2)} \left(\frac{0.072}{13} \right)^2$$

$$= 8,000 \text{ psi}$$

$$N_s^{cr} = \tau_{cr} t = 8,000 \times 0.072$$

$$= 580 \text{ lb/in (shear flow)}$$

NOTE: The preceding calculations do not account for initial imperfections.

Reference 1 does not specify a knock-down factor for short cylinders in shear. Therefore, check unwrapped flat panel in shear for comparison purposes.

$$b/a = 13/45 = 0.29$$

$$k_s = 5.8 \text{ (Ref. 4, Fig. 6.2.3-1)}$$

(flat plate with simply-supported sides)

$$\begin{aligned}\tau^{cr} &= \frac{k_s \pi^2 E}{12(1-\gamma^2)} \left(\frac{t}{b}\right)^2 \\ &= \frac{5.8}{27} \times 8,000 = 1700 \text{ psi}\end{aligned}$$

Obviously, curvature is quite significant. Therefore, account for initial imperfections by using the knock-down factor recommended for moderate length cylinders by Ref. 3, which is for the allowable shear stress (Equation 26).

$$\gamma^{3/4} = 0.67$$

$$\tau^{cr} = \frac{0.747 \gamma^{3/4} E}{(r/t)^{5/4} (\ell/r)^{1/2}}$$

Accordingly, the previously computed allowable shear stress becomes

$$\tau^{cr} = \gamma^{3/4} 7,654 = 0.67 \times 7,654 = 5,100 \text{ psi}$$

and the allowable shear flow becomes

$$N_s^{cr} = \gamma^{3/4} 580 = 0.67 \times 580 = 389 \text{ lb/in.}$$

General Shear Buckling
(See Reference 2, Figure 22d)

$$a = 45 \text{ in.}$$

$$b = 26 \text{ in.}$$

$$r = 21 \text{ in.}$$

$$t = 0.072 \text{ in.}$$

$$\begin{aligned}
 Z_b &= (b^2/rt) (1-\nu^2)^{1/2} \\
 &= [26/(21 \times 0.072)] (1-0.33^2)^{1/2} \\
 &= 424
 \end{aligned}$$

$$a/b = 45/26 = 1.73$$

$$\begin{aligned}
 D &= \frac{Et^3}{12(1-\nu^2)} = \frac{10.5 \times 10^6 \times 0.072^3}{12(1-0.33^2)} \\
 &= 366
 \end{aligned}$$

$$\begin{aligned}
 EI/bD &= 10.5 \times 10^6 \times 0.10478 / (26 \times 366) \\
 &= 115
 \end{aligned}$$

$$k_s = 120$$

$$\gamma^{3/4} = 0.67$$

$$\begin{aligned}
 \tau_{GI}^{cr} &\approx \frac{k_s \gamma^{3/4} \pi^2 E}{12(1-\nu^2)} \left(\frac{t}{b}\right)^2 \quad (\text{general instability}) \\
 &\approx \frac{120 \times 0.67 \pi^2 \times 10.5 \times 10^6}{12(1-0.33^2)} \left(\frac{0.72}{26}\right)^2 \\
 &\approx 5,985 \text{ psi}
 \end{aligned}$$

$$\begin{aligned}
 N_{s_{GI}}^{cr} &= 5,985 \times 0.072 \\
 &\approx 430 \text{ lb/in.}
 \end{aligned}$$

Discussion of Mid-Ring

The ratio of allowable shear flow for general shear instability to local shear instability is

$$\begin{aligned}
 R &= N_{s_{GI}}^{cr} / N_s^{cr} = 430/389 \\
 &= 1.1
 \end{aligned}$$

Therefore, the ring I should be left as is.

Local Compression Buckling

(The local compressive strength is determined for reference purposes.)

$$r/t = 21/0.072 = 292$$

$$\gamma = 0.41 \text{ (Reference 4, Figure 2)}$$

$$Z_b = 106 \text{ (Reference Page 5 of this report)}$$

$$\gamma Z_b = 0.41 \times 106 = 43$$

$$k_x = 25$$

$$N_{x_{\text{local}}}^{\text{cr}} = k_x \frac{\pi^2 D}{\ell^2} = 25 \frac{\pi^2 \times 366}{13^2}$$

$$= 534 \text{ lb/in.}$$

According to the table on page 11 of Reference 2, the stiffener at mid-length of the curved panel does not increase the buckling stress. Therefore,

$$N_{x_{\text{GI}}}^{\text{cr}} \equiv N_{x_{\text{local}}}^{\text{cr}} = 534 \text{ lb/in.}$$

F-16 GRAPHITE/THERMOPLASTIC AMMUNITION BAY DOOR

Material properties/graphite/thermoplastic (current)

$$F_{11}^{\text{tu}} = F_{11}^{\text{cu}} = 170 \text{ ksi}$$

$$F_{22}^{\text{tu}} = 5 \text{ ksi}$$

$$F_{22}^{\text{cu}} = 15 \text{ ksi}$$

$$F_{12}^{\text{su}} = 10 \text{ ksi}$$

$$\epsilon_{11}^{\text{tu}} = 0.0113$$

$$\epsilon_{22}^{\text{tu}} = 0.0033$$

$$\epsilon_{11}^{\text{cu}} = 0.0113$$

$$\epsilon_{22}^{\text{cu}} = 0.0100$$

$$\gamma_{12} = 0.0116$$

$$E_{11}^t = E_{11}^c = 15 \times 10^6 \text{ psi}$$

$$E_{22}^t = E_{22}^c = 1.5 \times 10^6 \text{ psi}$$

$$G_{12} = 0.86 \times 10^6 \text{ psi}$$

$$\gamma_{12} = 0.27$$

For determining elastic constants and strengths of laminates, neglect plasticity effects in 22, 12 - directions. This is not too unconservative since σ_{22}, σ_{12} stresses will not be very large.

Therefore,

for SQ5 computer code (using lamination theory)

$$\begin{aligned} \epsilon_{11}^{t,c} &= F_{11}^{t,c} / E_{11}^{t,c} = 170,000 / 15 \times 10^6 \\ &= 0.0113 \text{ (elastic)} \end{aligned}$$

$$\begin{aligned} \epsilon_{22}^t &= F_{22}^t / E_{22}^t = 5000 / 1.5 \times 10^6 \\ &= 0.0033 \text{ (elastic)} \end{aligned}$$

$$\begin{aligned} \gamma_{12} &= F_{12}^{su} / G_{12} = 10,000 / 0.86 \times 10^6 \\ &= 0.0116 \text{ (elastic)} \end{aligned}$$

NOTE: Elastically determined strains are used, but stress-strain curve to failure may be nonlinear.

Determine compressive and shear stiffnesses by lamination theory for

$$\begin{array}{ll} [\pm 45/0_2/\mp 45]_T & [\pm 45/0_8/\mp 45] \\ [\pm 45/0_4/\mp 45]_T & [\pm 45/0_{10}/\mp 45] \\ [\pm 45/0_6/\mp 45]_T & [\pm 45/0_{12}/\mp 45] \end{array}$$

which are shown plotted with those of 2024 aluminum alloy in Figures A-1, A-2, and A-3.

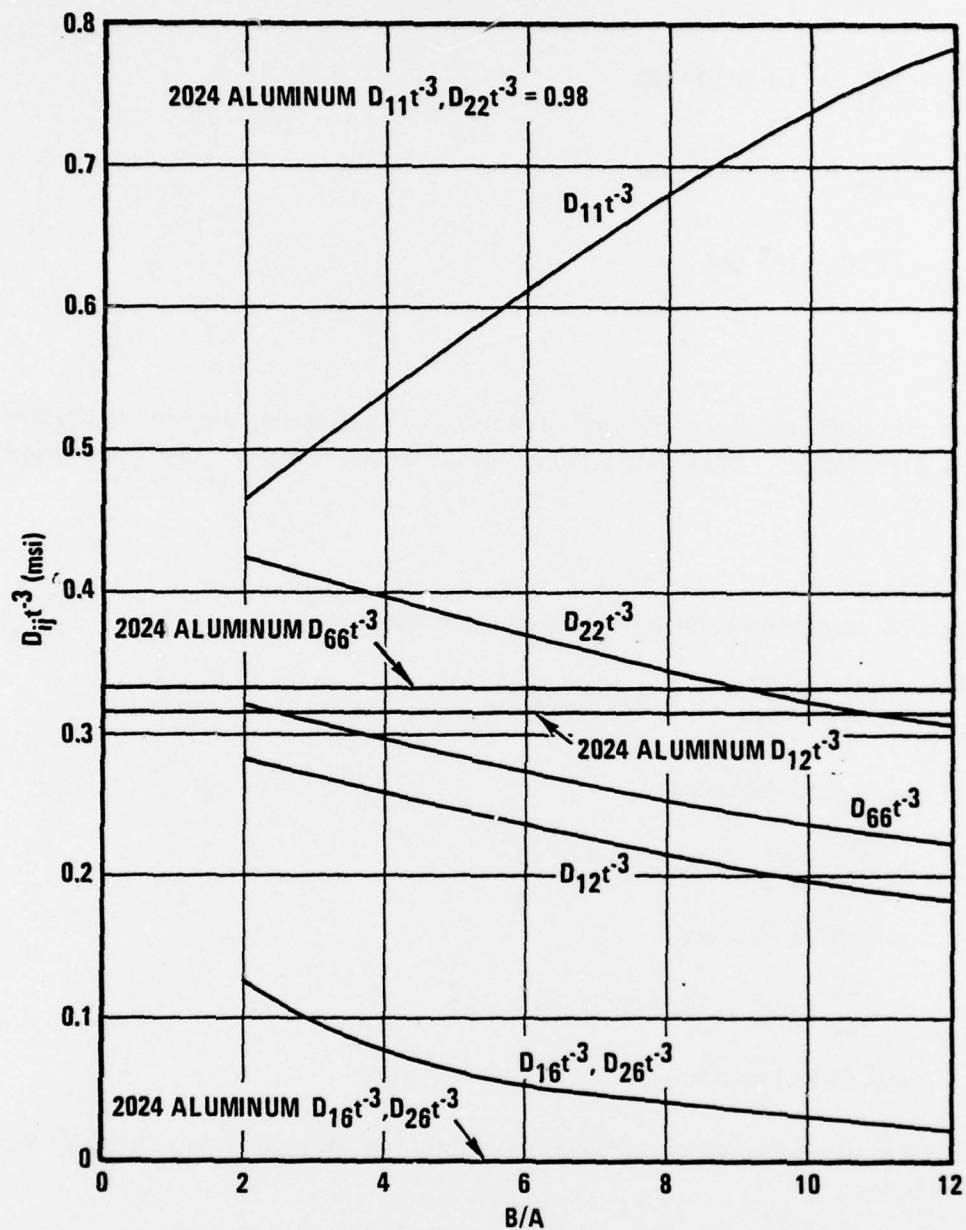


Figure A-1. Flexural Elastic Constants for A-S/Polysulfone Graphite/
Thermoplastic $[\pm 45^\circ_A / 0^\circ_B / \mp 45^\circ_A]_T$

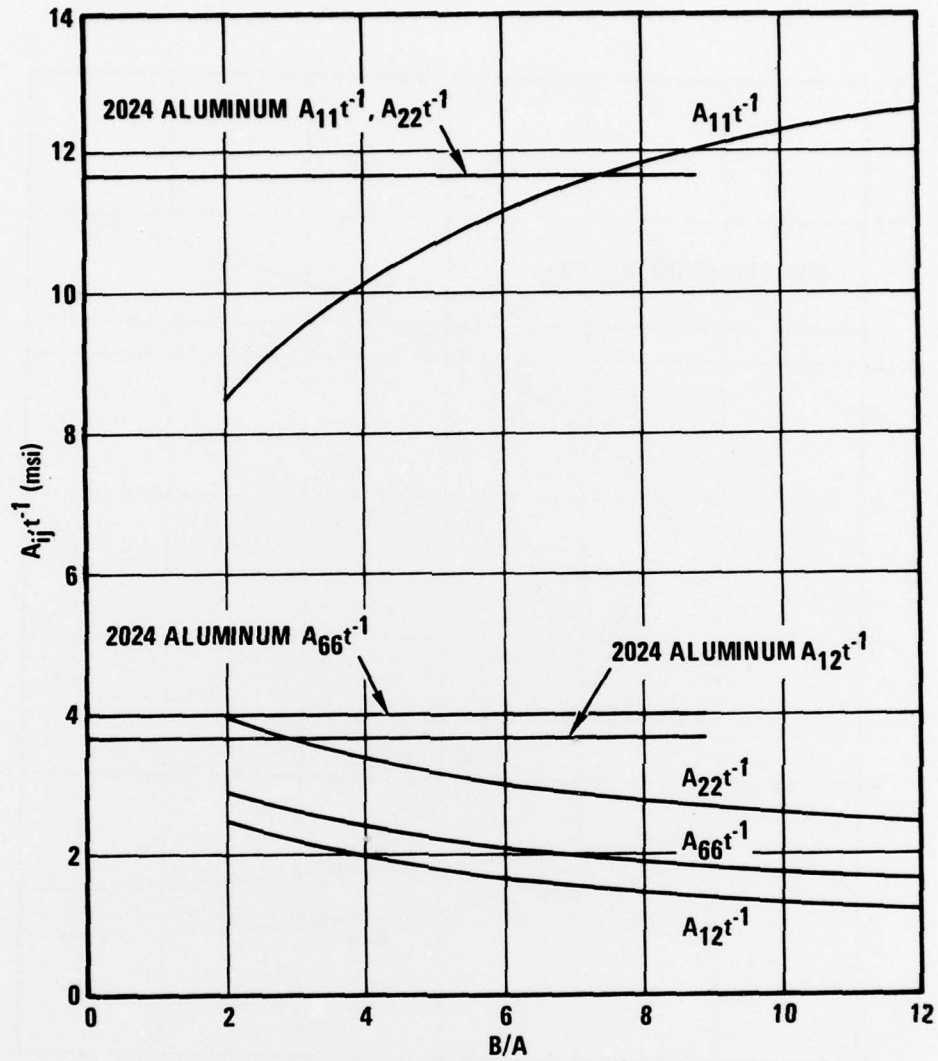


Figure A-2. Extensional Elastic Constants for A-S/Polysulfone Graphite/
Thermoplastic $[\pm 45_A/0_B/\mp 45_A]_T$

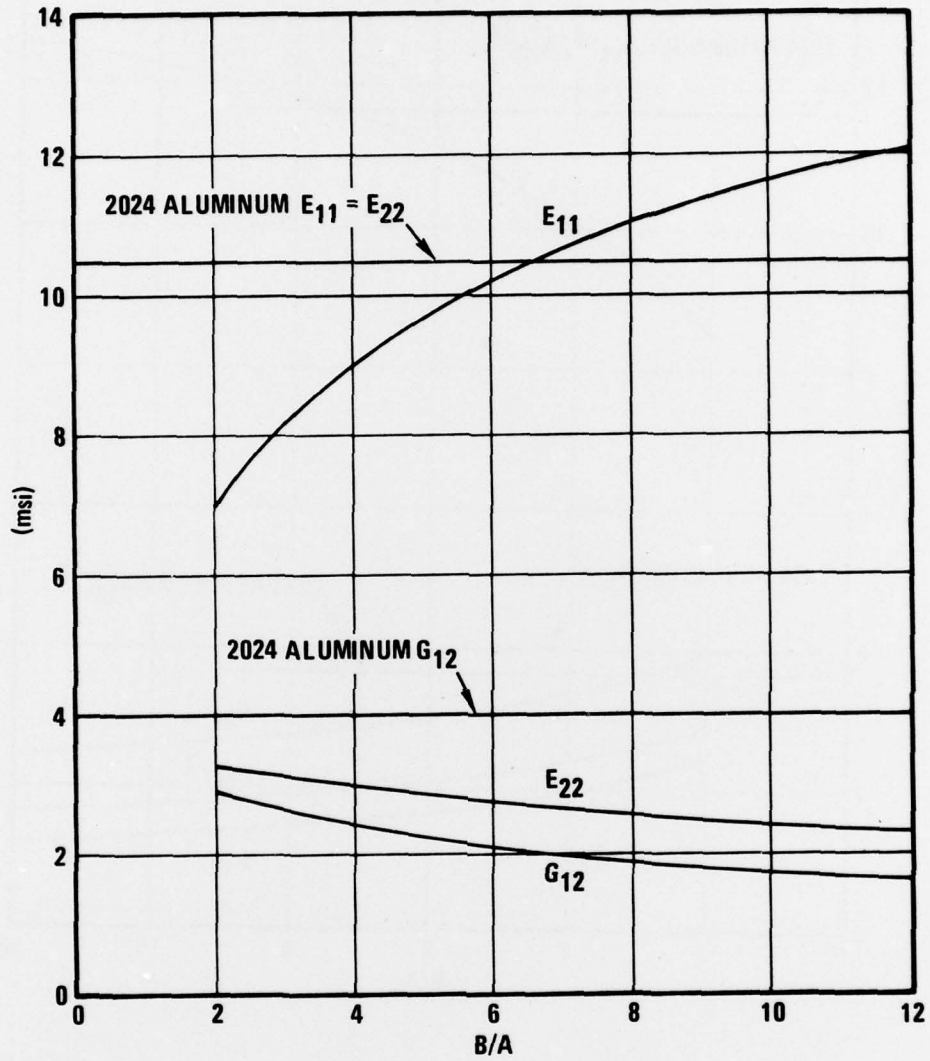


Figure A-3. Elastic Moduli for A-S/Polysulfone Graphite/Thermoplastic
 $[\pm 45_A / 0_B / \mp 45_A]_T$

Composite Thickness Selection

Use the stacking sequence

$$[\pm 45_2/0_7/+45_2]_T$$

where

$$B/A = 3.5$$

$$t = 0.075 \text{ in.}$$

$$D_{11} = 219 \text{ lb-in.}$$

$$D_{22} = 170 \text{ lb-in.}$$

$$D_{12} = 112 \text{ lb-in.}$$

$$D_{66} = 128 \text{ lb-in.}$$

See Figure A-1

For buckling in shear, it is most important that the D_{66} term be approximately equivalent to that for the aluminum skin ($D_{66}=125\text{lb-in.}$). The comparison is

$$D_{66 \text{ comp}} / D_{66 \text{ alum}} = 128/125 = 1.02$$

which looks satisfactory, even though the remaining D_{ij} terms for the composite are less than those of the 2024 aluminum alloy.

Accordingly, this laminate will be used for the test component. The drawing of the component is shown in Figure 3-2.

References

1. G. Gerard and H. Becker, Handbook of Structural Stability, Part III, "Buckling of Curved Plates and Shells," NACA TN 3783, August 1957.
2. H. Becker Handbook of Structural Stability, Part II, "Buckling of Composite Elements," NACA TN 3782, July 1957.
3. NASA Space Vehicle Design Criteria (Structures), NASA SP-8007, August 1968.
4. General Dynamics Fort Worth Structures Manual, 1960.